Aerosol Retrievals via Lidar

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with inputs from
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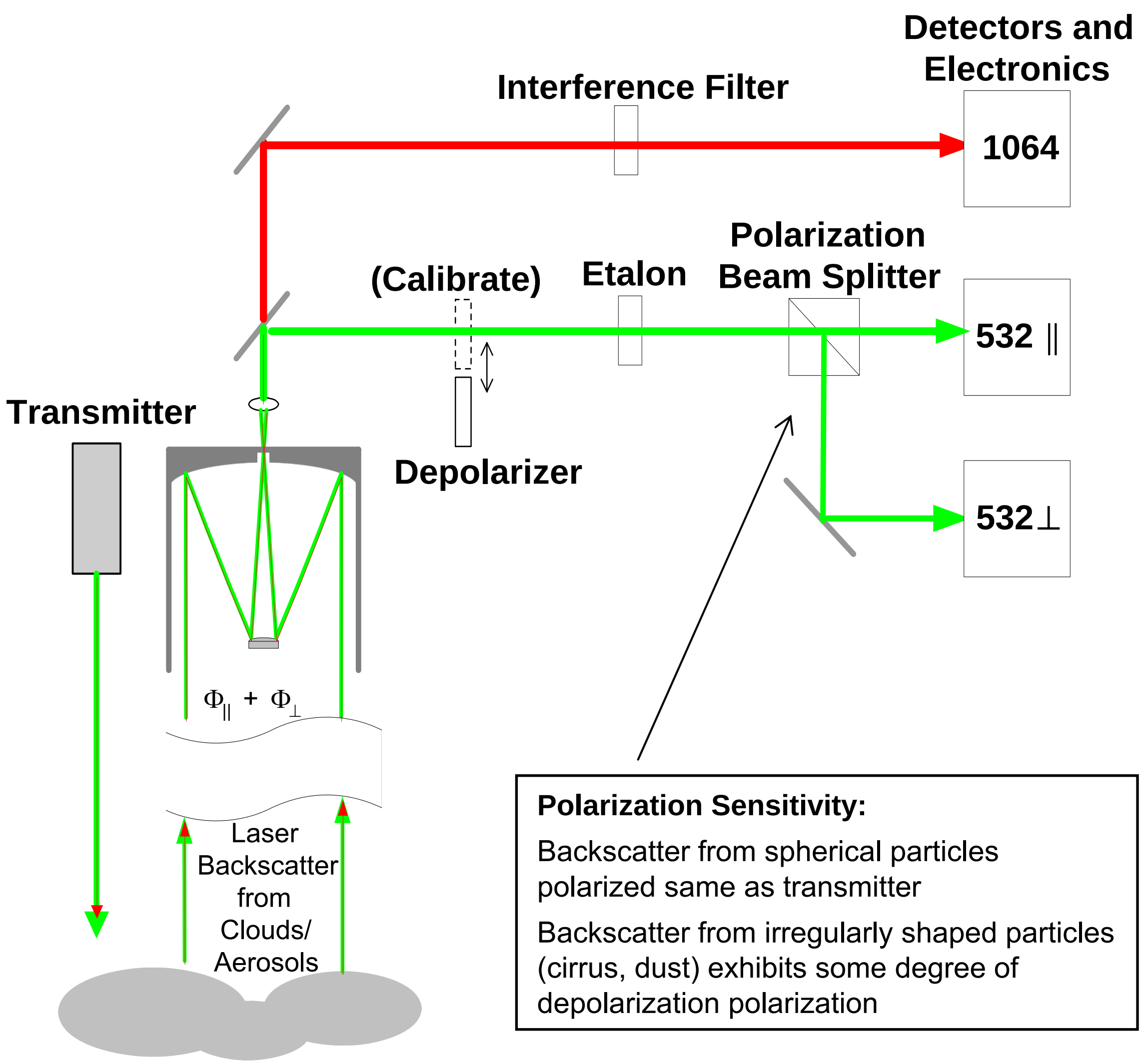
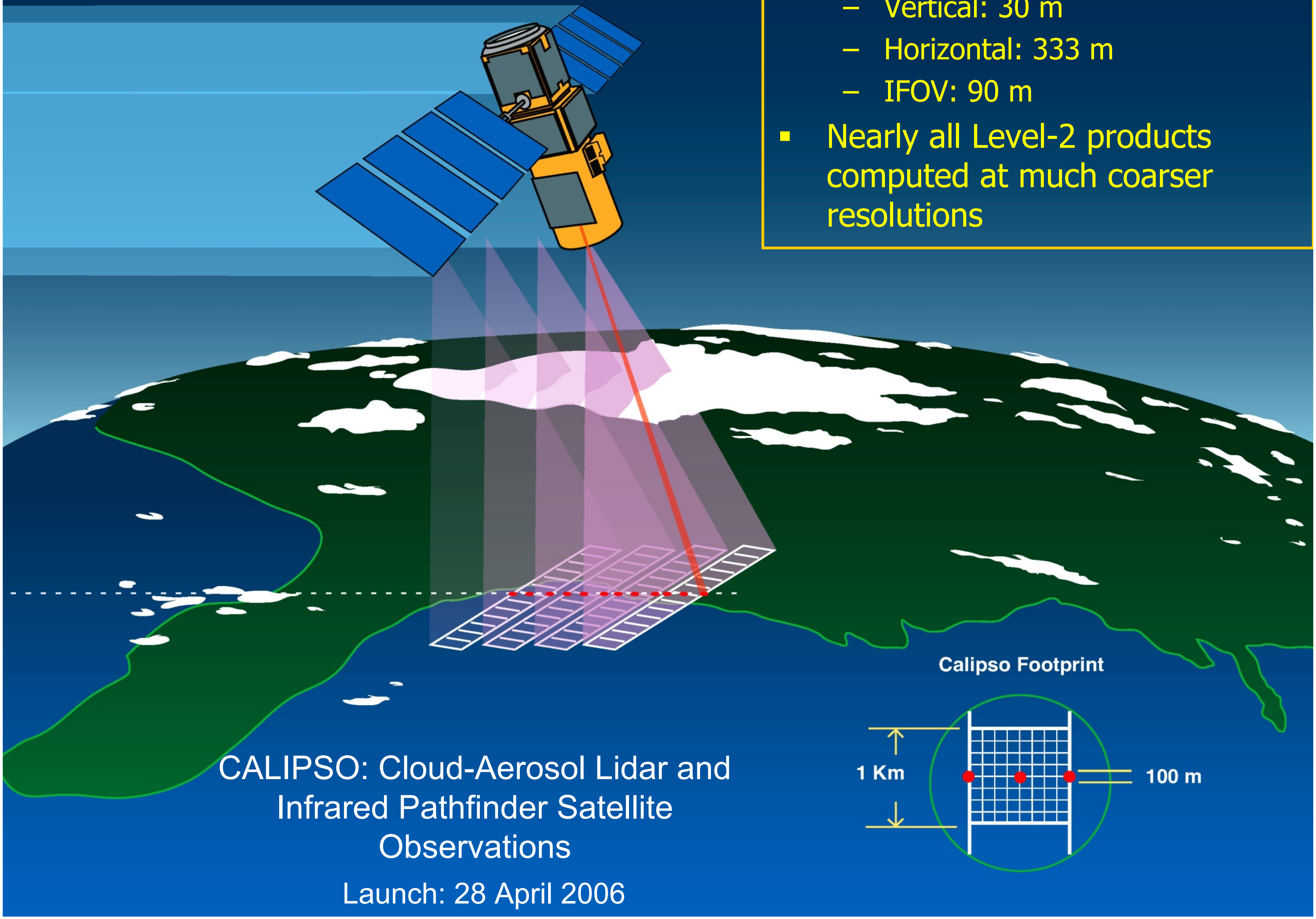
Backscatter Lidar



- Time-of-flight ranging technique
- Employs pulsed laser transmitter
- Measures vertically resolved profiles of backscatter from molecules and aerosol/cloud particulates for each laser shot
  - Data may be averaged vertically and horizontally (combining profiles from consecutive shots)
- Wavelengths. For ACE, probably limited to those available from high-reliability Nd:YAG or Nd:YLF lasers:
  - 1064, 532 nm
  - 1064, 532, 355 nm

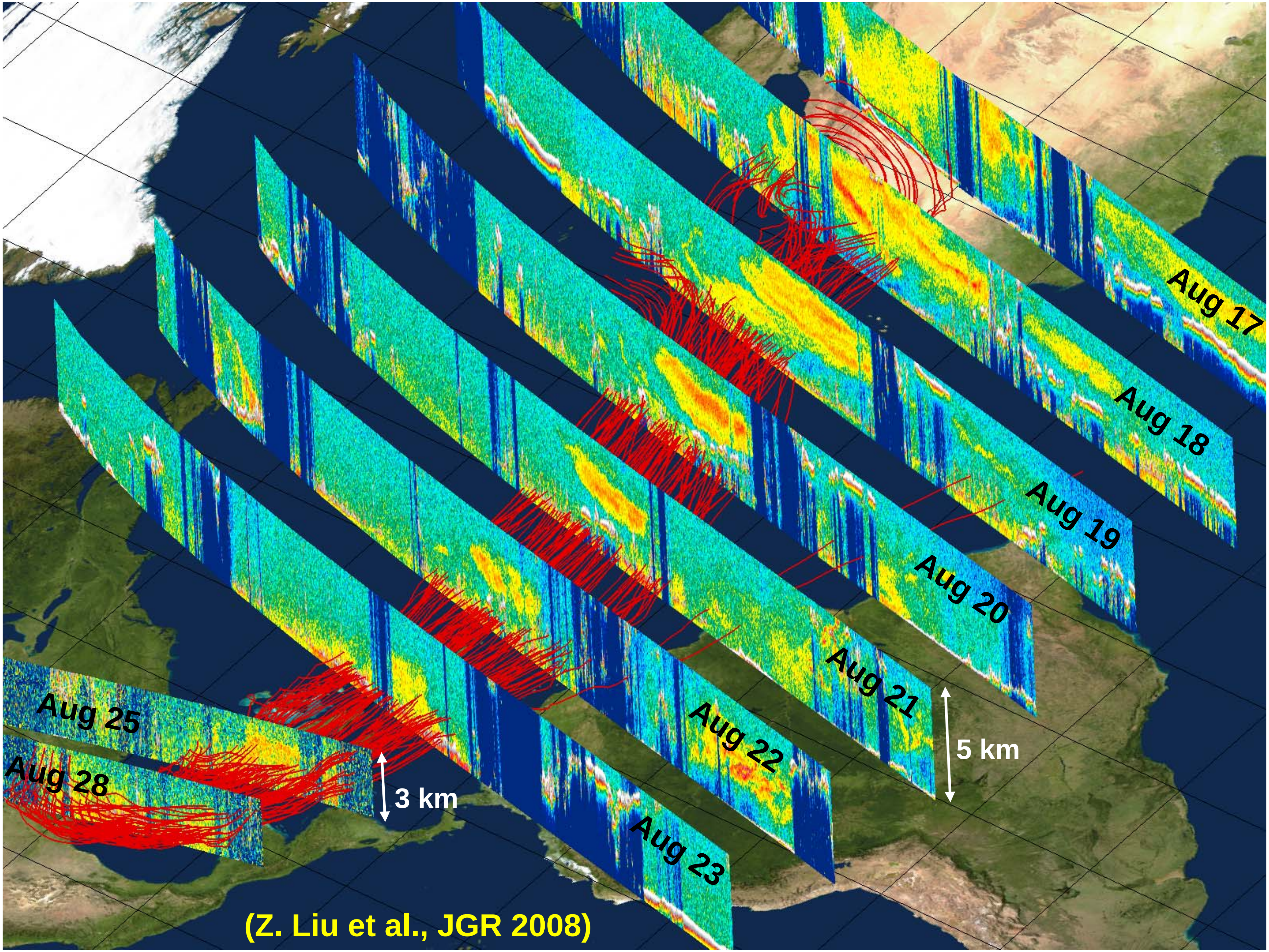
CALIOP Lidar on CALIPSO

- Fundamental sampling
  - Vertical: 30 m
  - Horizontal: 333 m
  - IFOV: 90 m
- Nearly all Level-2 products computed at much coarser resolutions



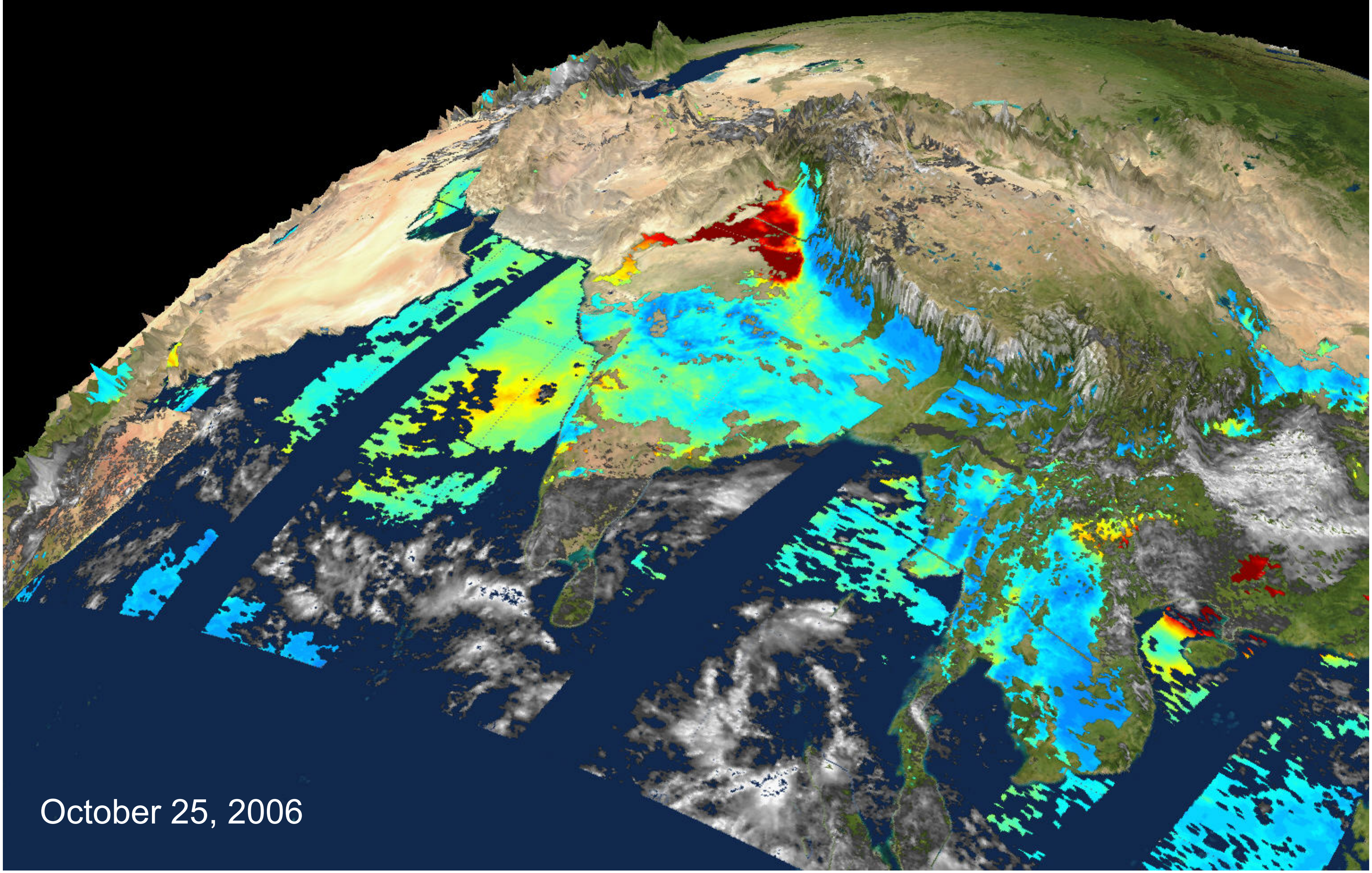
CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

Launch: 28 April 2006

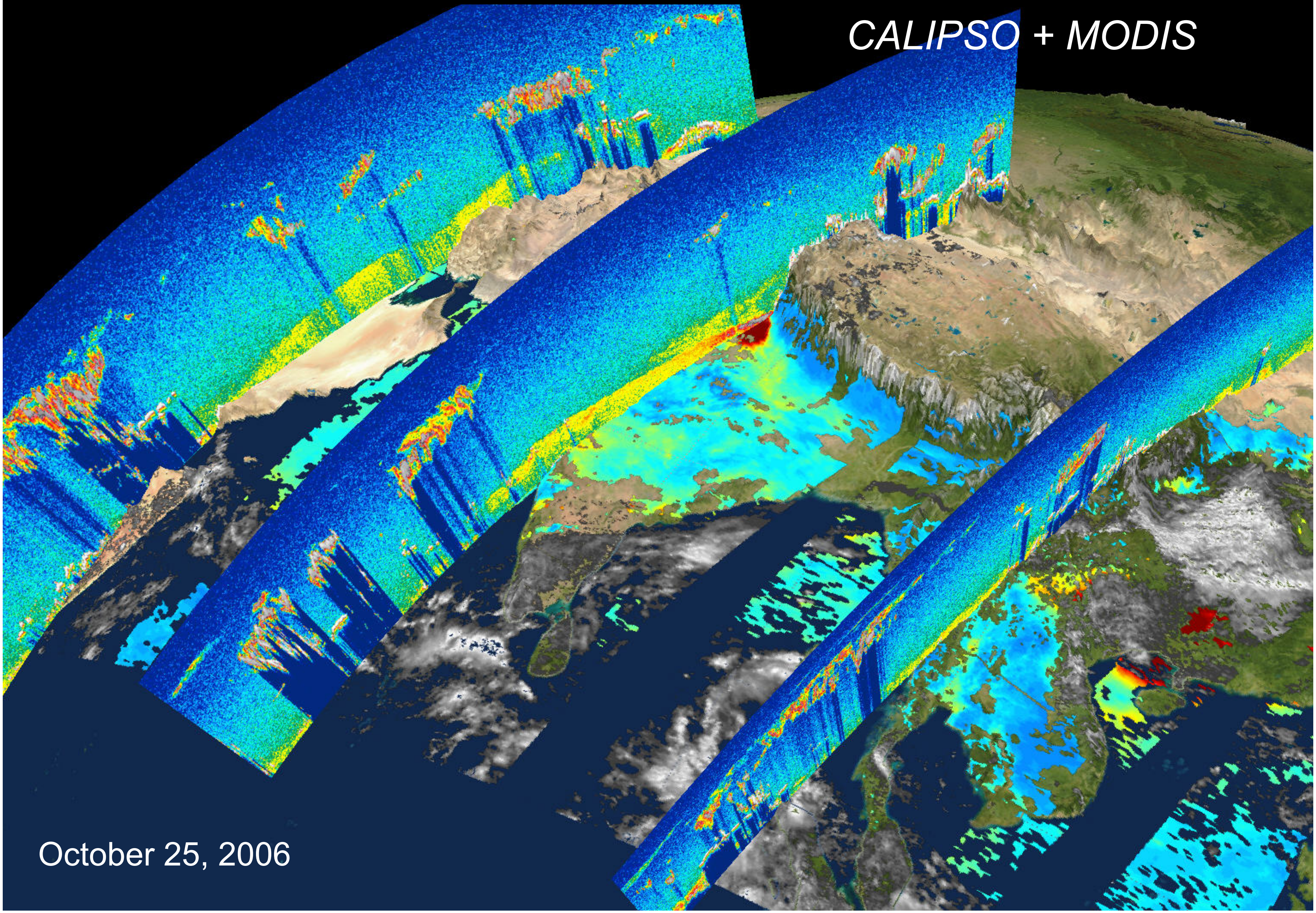

Aug 17
Aug 18
Aug 19
Aug 20
Aug 21
Aug 22
Aug 23
Aug 25
Aug 28
5 km
3 km
(Z. Liu et al., JGR 2008)

Aerosol and Cloud Observations over South Asia

MODIS



Aerosol and Cloud Observations over South Asia

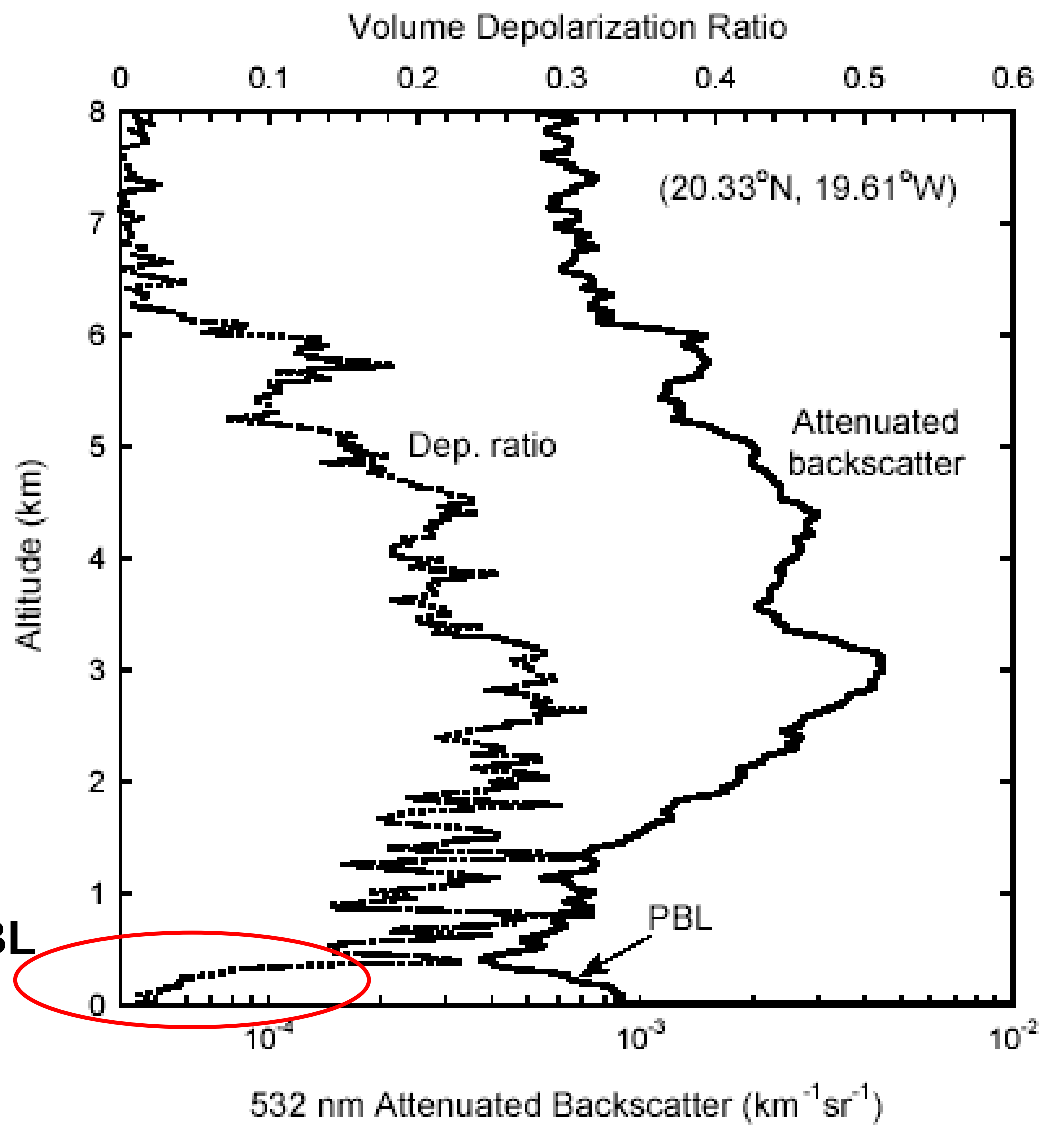


Basic Lidar Data Products

- Profile products
  - Fundamental products:
    - Attenuated backscatter profile
    - Total (molecular plus particulate) depolarization profile
  - Retrieved products:
    - Aerosol/cloud backscatter profile
    - Aerosol/cloud extinction profile
    - Aerosol/cloud depolarization profile
- Layer heights
  - BL layer height
  - Top and bottom height of elevated aerosol/cloud layers
- Layer average products
  - Layer integrated backscatter
  - Aerosol optical depth
  - Layer average depolarization, wavelength dependence, etc.

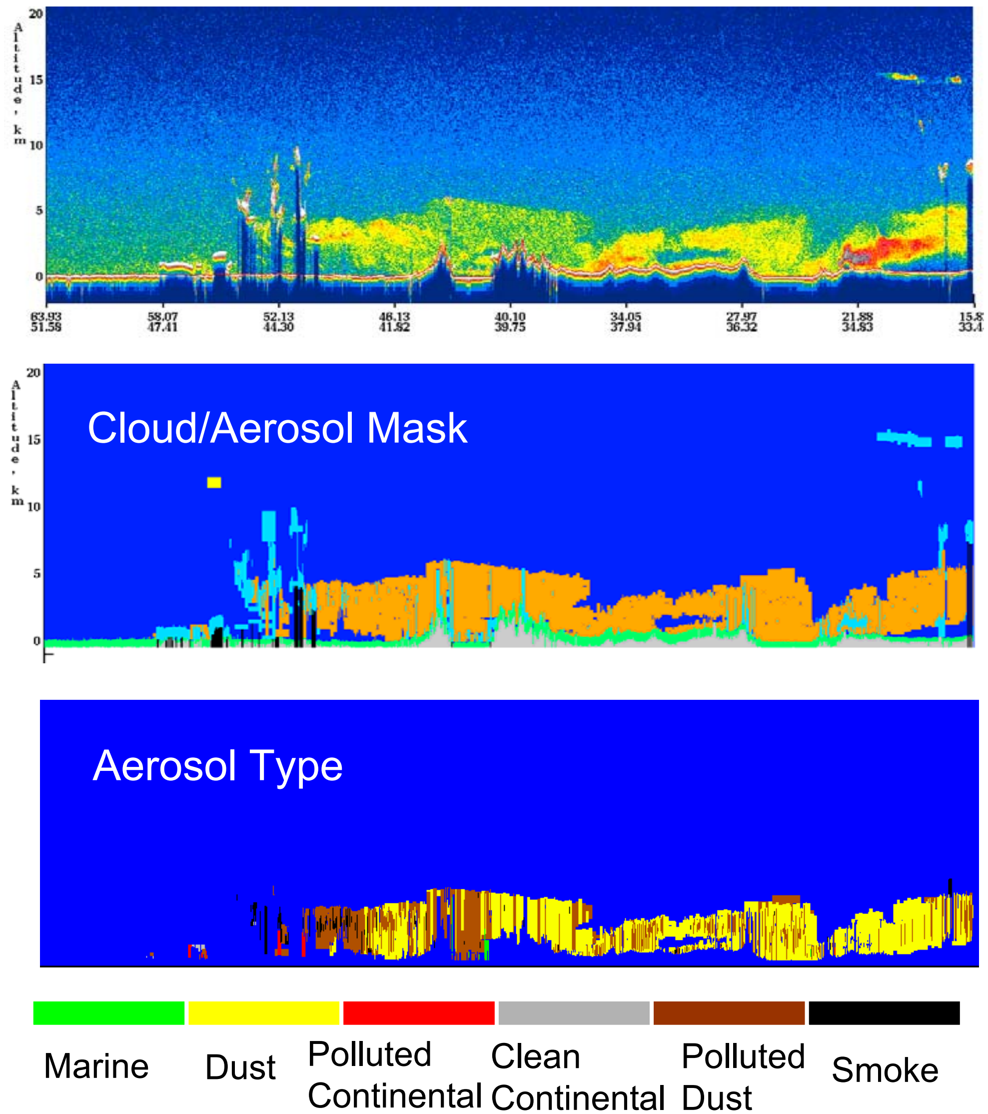
532 nm Dust Profiles from CALIOP

humid marine BL



Feature Mask and Aerosol Typing

- Aerosols are classified into 6 subtypes
- Algorithm based on lidar 532/1064 and 532 depol data
- Needed to identify extinction-to-backscatter ratio for extinction retrieval
- Aids analysis of radiative and chemical properties
- Inferred information on effective radii and composition can aid air quality applications



Data Resolution and Averaging

- Fundamental (raw) resolutions
  - Vertical: 15-100 m (30 m for CALIPSO)
  - Horizontal: 1 laser shot
    - 175 m for GLAS (40 shots/sec)
    - 333 m for CALIPSO (21 shots/sec)
  - IFOV: depends on laser divergence and telescope FOV.
    - 90 m for CALIPSO

- Data Averaging
  - Only the strongest features (e.g., BL clouds) can be detected at full resolution
  - Averaging done in the horizontal and vertical to improve SNR for retrievals
  - CALIPSO uses a complex multi-grid averaging scheme to identify and compute layer products on 5, 20, and 80 km horizontal grids
  - CALIPSO Level-2 aerosol profile products are 40-km horizontal resolution

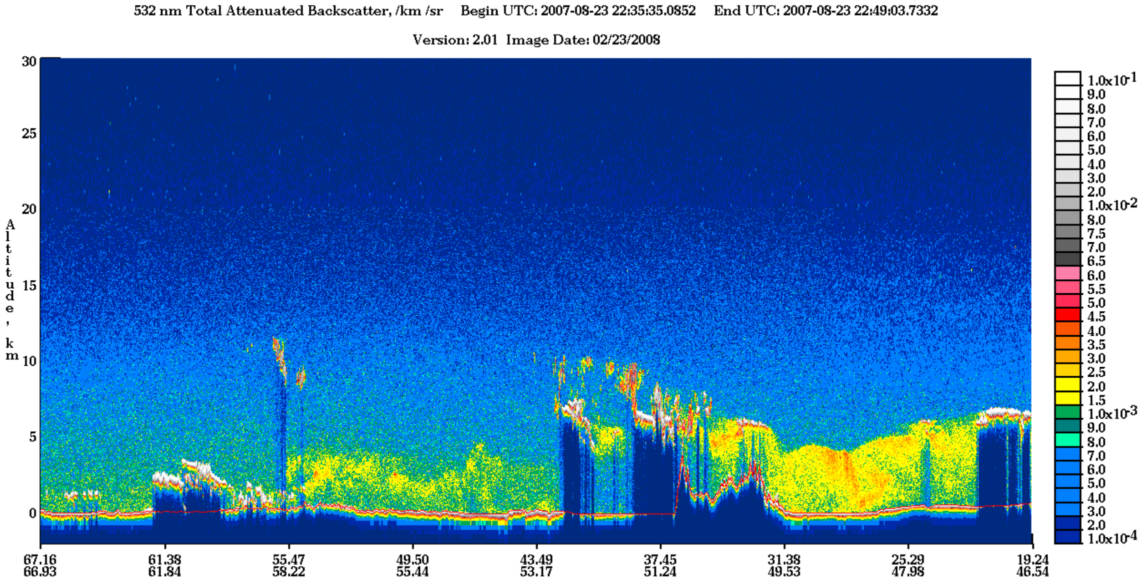
Cross-Cutting Applications

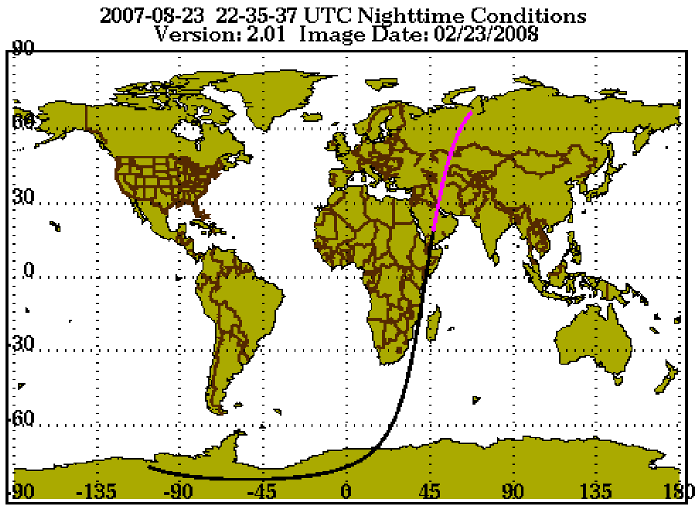
- Possible to also add channels for
  - Ocean subsurface measurements
  - Vegetation canopy
- Requires
  - Adding receiver channels
  - Short laser pulse widths

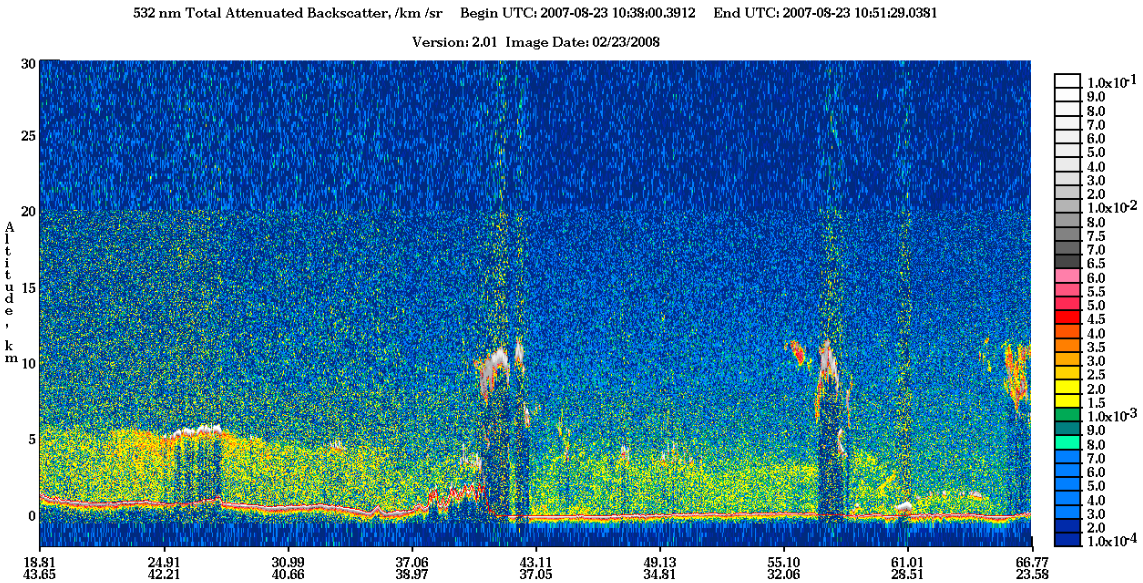
Backscatter Lidar Retrieval Issues

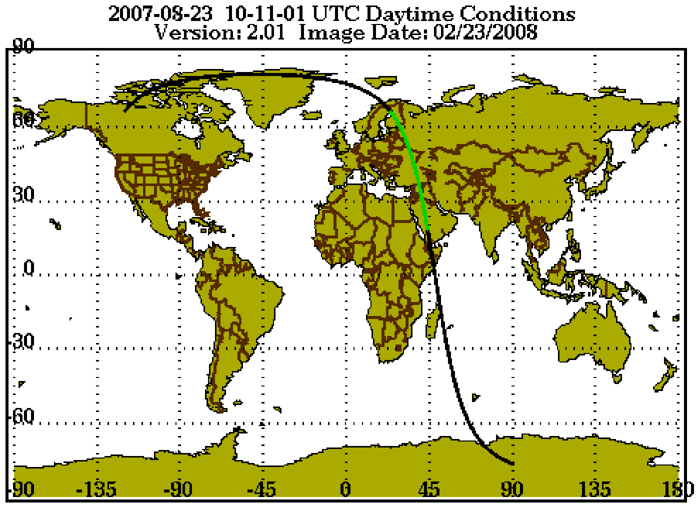
- Daytime SNR
- Calibration
- Structural error due to error in assumptions

Night vs. Day


532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2007-08-23 22:35:35.0852 End UTC: 2007-08-23 22:49:03.7332
Version: 2.01 Image Date: 02/23/2008
Altitude, km


2007-08-23 22-35-37 UTC Nighttime Conditions
Version: 2.01 Image Date: 02/23/2008


532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2007-08-23 10:38:00.3912 End UTC: 2007-08-23 10:51:29.0381
Version: 2.01 Image Date: 02/23/2008
Altitude, km


2007-08-23 10-11-01 UTC Daytime Conditions
Version: 2.01 Image Date: 02/23/2008

Day SNR

- Daytime SNR can be low due to noise in solar background.
- Noise can be reduced via narrowband solar rejection filters
- CALIPSO and GLAS filters are about as narrow (~40 GHz) as the laser linewidths allow
  - Lasers are multi-mode
- ACE lidar can be designed to do much better during day
  - Use single-frequency laser and ultra narrow solar rejection filter in receiver
  - Use higher laser energy

Calibration

- Signal is calibrated to estimated backscatter at some point in the profile
  - Molecular backscatter estimated from model (GMAO)
  - Aerosol backscatter difficult to estimate. Calibration region chosen where aerosol backscatter is very low.

- CALIPSO calibrated over the 30-34 km region on night side of orbit
  - Validation data show calibration has bias of ~5% in mid/low latitudes. <u>Quite good!</u>
  - Bias believed to be due to backscatter from stratospheric aerosol, assumed zero in current version of algorithm
  - Future versions of calibration require aerosol model that varies with latitude and season

- Solar background noise makes this calibration approach impractical for day side of orbit.
  - On CALIPSO, night calibration interpolated across day side of orbit
  - Thermally induced alignment changes have complicated application of night calibration to day side of orbit.
  - CALIPSO team has devised a scheme for estimating and correcting day calibration errors due to alignment changes
  - ACE lidar can be designed to reduce this problem

Structural Error

- Backscatter lidar measures **total attenuated backscatter**
  - Measured Signal = (aerosol + molecular backscatter) x (two-way transmittance from lidar to scattering volume)

- ***Aerosol backscatter*** and ***aerosol extinction*** must be retrieved from total attenuated backscatter

- Retrieval relies upon assumption of the extinction-to-backscatter ratio
  - Extinction-to-backscatter ratio = “lidar ratio” = S_a

Structural Error in Retrieval: 1 equation, 2 unknowns

Measured Signal | **Range from Instrument** | **Calibration Constant** | **Molecular Backscatter Coefficient** | **Molecular Extinction Coefficient**

← **Known**

Determined from measured signals and meteorological data

$$P(r) = \frac{C}{r^2}\left[\beta_m(r) + \beta_p(r)\right]\exp\left\{-2\int_0^r\left[\sigma_m(r') + \sigma_p(r')\right]dr'\right\}$$

Particulate Backscatter Coefficient | **Particulate Extinction Coefficient**

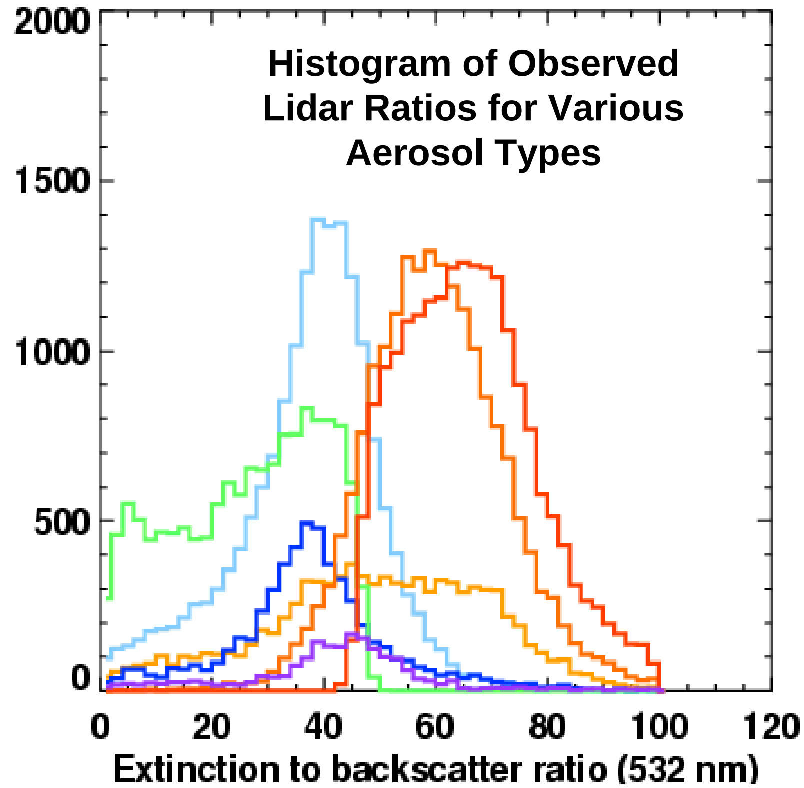
← **Retrieved Parameters**

$$\frac{\sigma_p(r)}{\beta_p(r)} = S_p$$

← Assumption of value for extinction-to-backscatter (S_p) ratio required for backscatter lidar retrieval

Structural Error

- Uncertainty in lidar ratio (S_a) can be a significant source of error in backscatter lidar retrievals
  - For aerosols: $10 < S_{a,\ 532\ nm} < 100$
- Selection of lidar ratio can be narrowed by inferring aerosol type
- Lidar observables can aid in selection
  - Chicken-and-egg problem
  - Need Level-2 aerosol products to better infer aerosol type
  - Need aerosol type to retrieve Level-2 products
- Can also use other information to narrow selection
  - Location (e.g., ocean vs. land)
  - Information from models or other sensors



Constrained Retrieval

- Adding column aerosol optical depth (AOD) constraint can improve accuracy of lidar retrieval
  - MODIS or PARASOL AOD as constraint on CALIPSO retrieval
  - Polarimeter AOD as constraint on ACE lidar retrieval

- Effectively enables estimate of column-average lidar ratio for use in Level-2 lidar extinction and backscatter retrieval
  - Generally improves extinction and backscatter retrievals
  - However, vertical variation in lidar ratio still leads to structural error. Studies show significant vertical variation in 40% of cases.

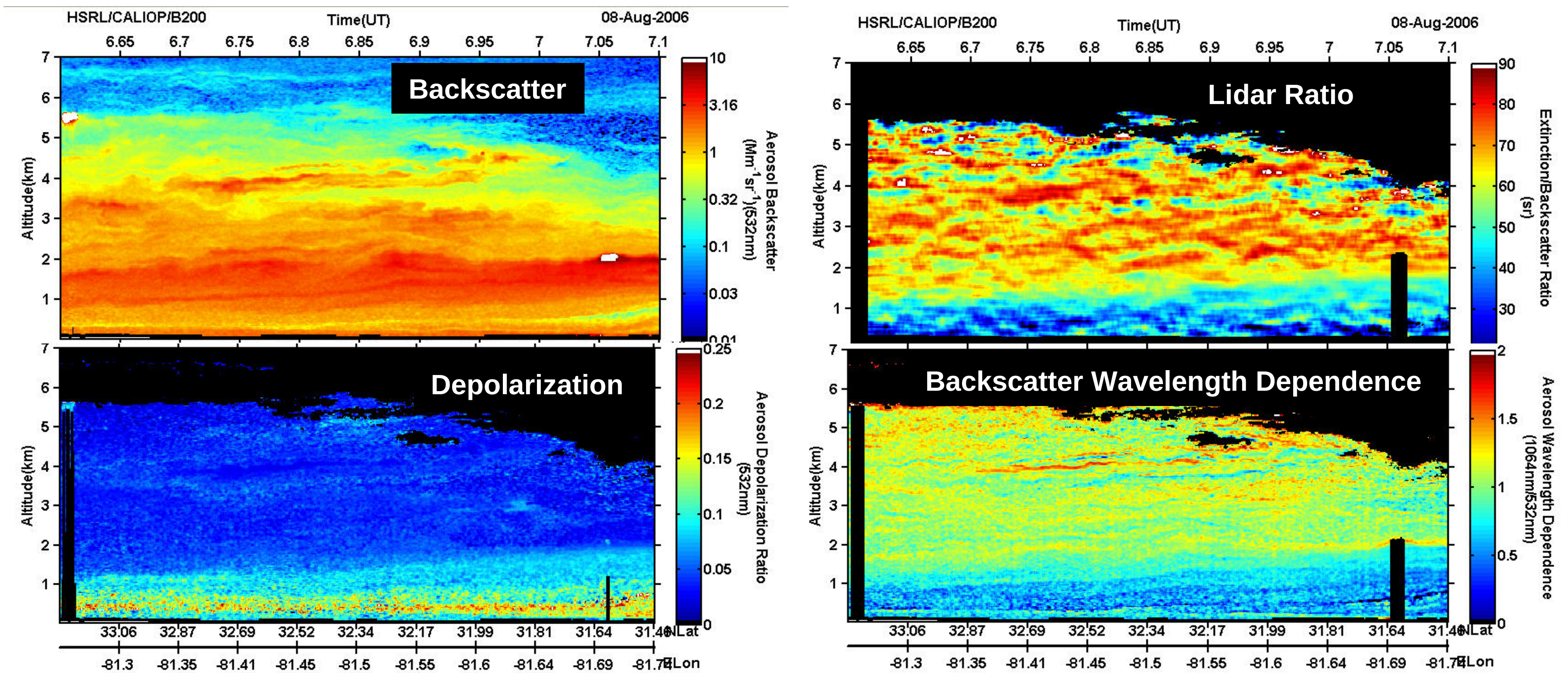
- Constrained retrieval only possible where accurate constraint is available. Problem areas include
  - Sun glint regions of the ocean
  - Bright surfaces
  - Near clouds (3-D cloud scatter effects bias AOD)

Error in S_a and Extinction Using Constrained Retrieval

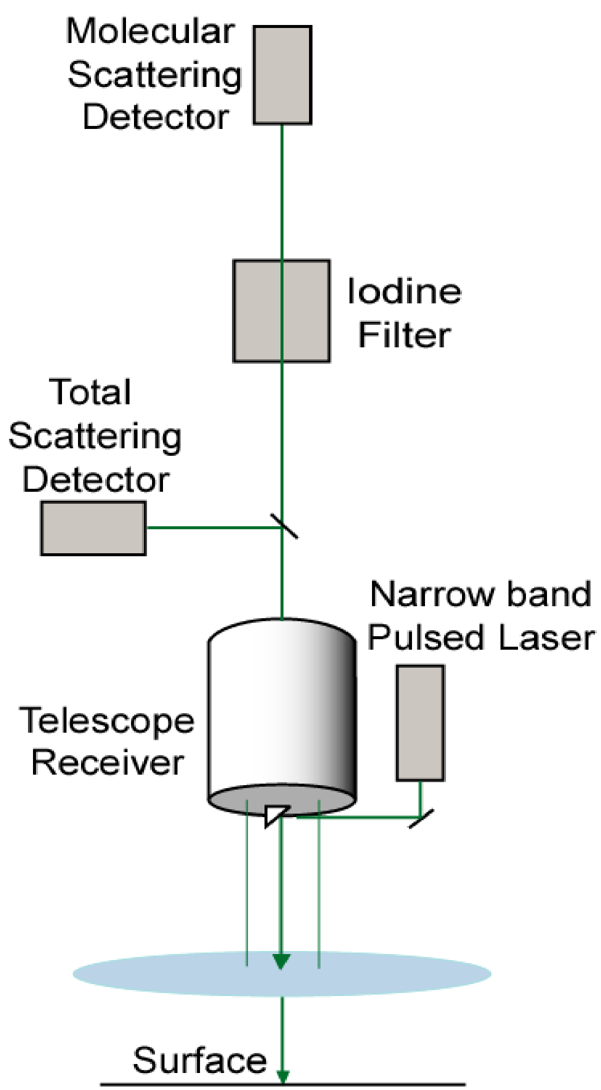
Vertical variability of the lidar ratio is examined using HSRL data acquired during field campaigns from 2006 and 2007

- S_a varies by more than +/- 10 sr about 40% of the time over 0-6 km layer
- Aerosol extinction derived using HSRL backscatter and the layer AOT constraint differs by more than +/15% from the aerosol extinction derived directly using the HSRL technique about 40% of the time

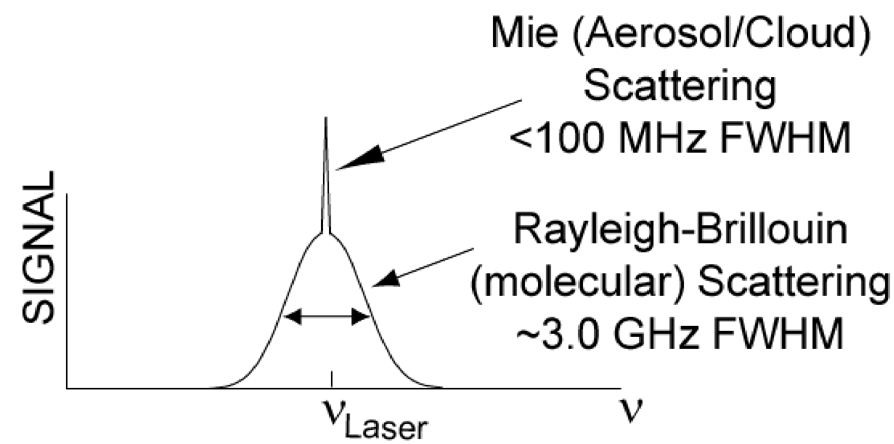
Example: Vertical variability of lidar ratio and other intensive aerosol parameters (Aug. 8, 2006)



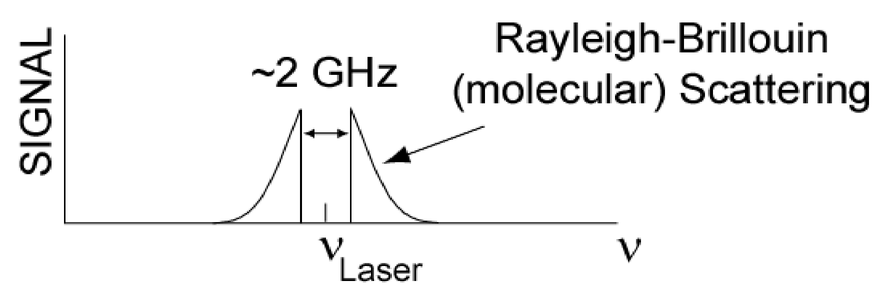
HSRL measurement concept:
(one possible realization at 532 nm)



Atmospheric Scattering



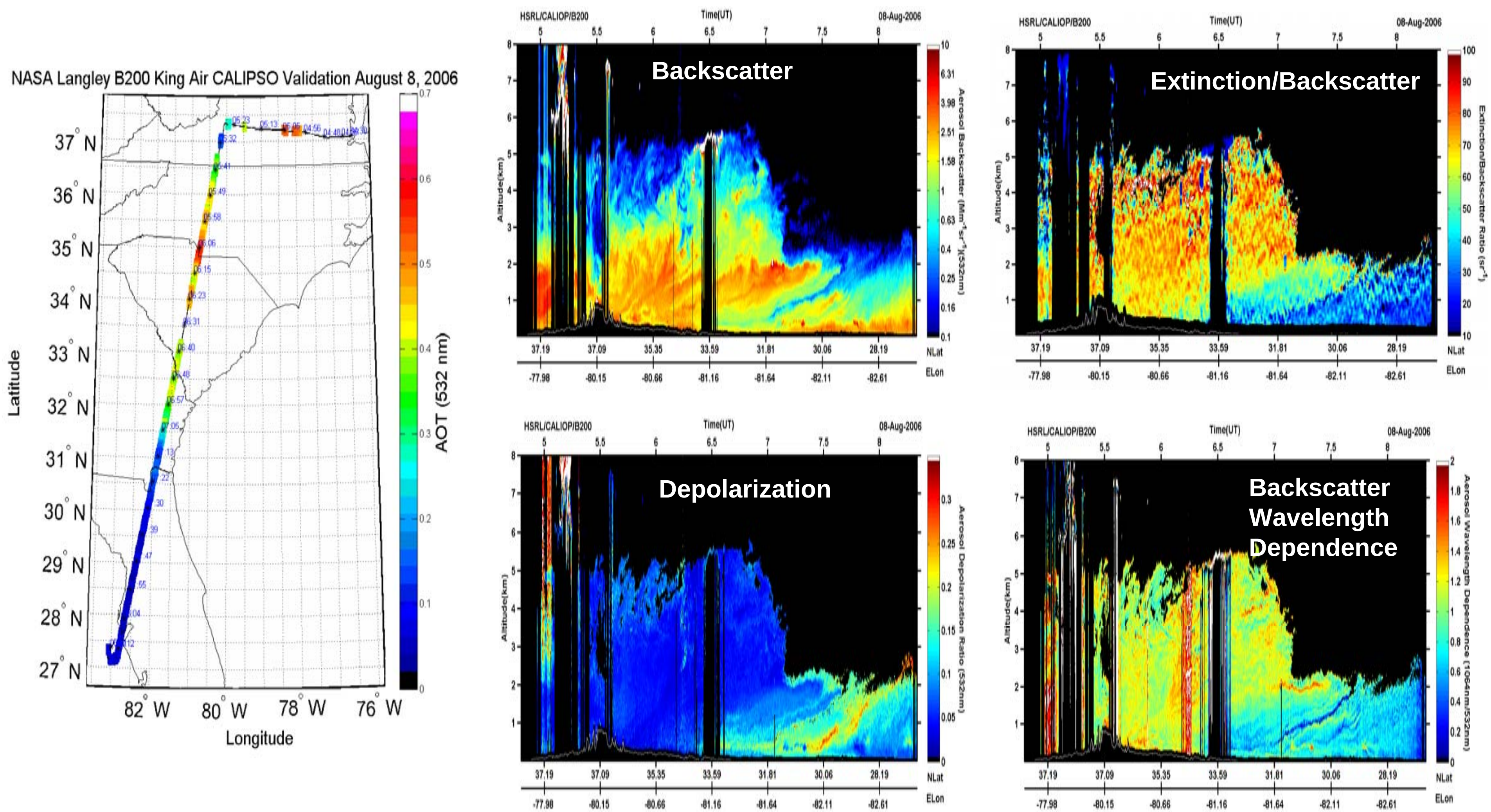
Effect of Iodine Vapor Notch Filter



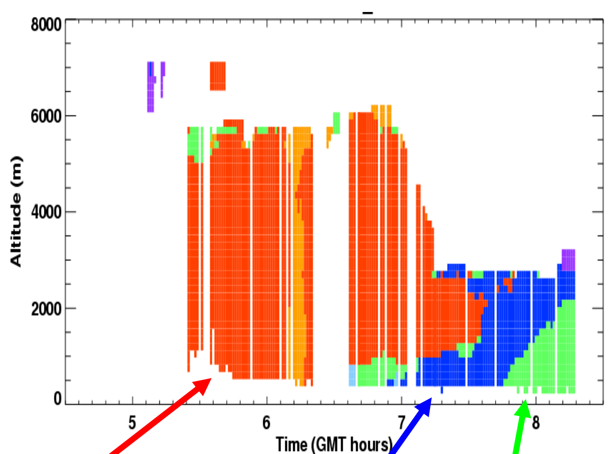
HSRL Advantages

- Can be internally calibrated, day or night
- Independent and more accurate aerosol/cloud extinction and backscatter profiles (no assumptions)
- More straightforward retrievals
- Higher information content for aerosol typing

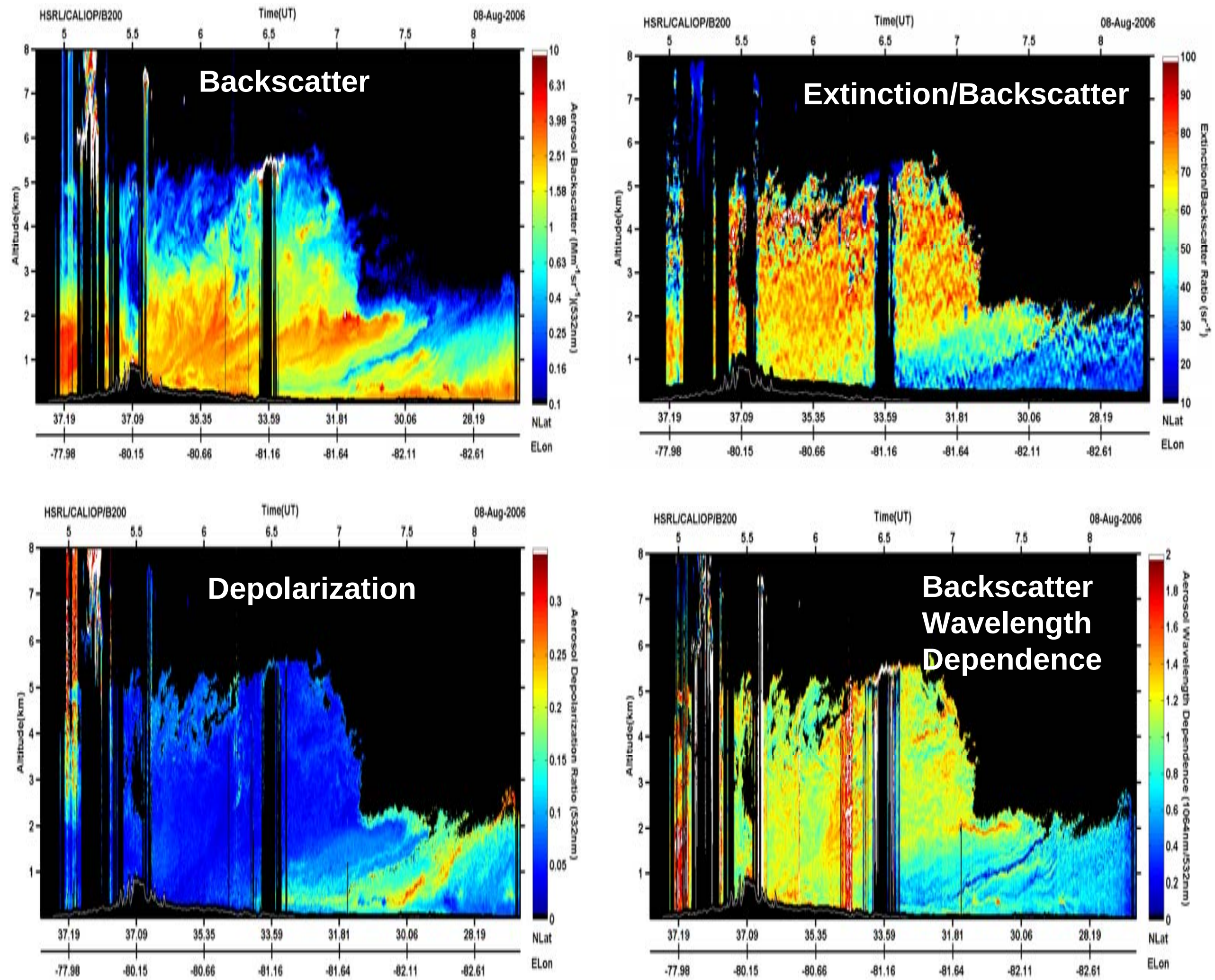
HSRL – more accurate information on aerosol extinction, optical depth, and type



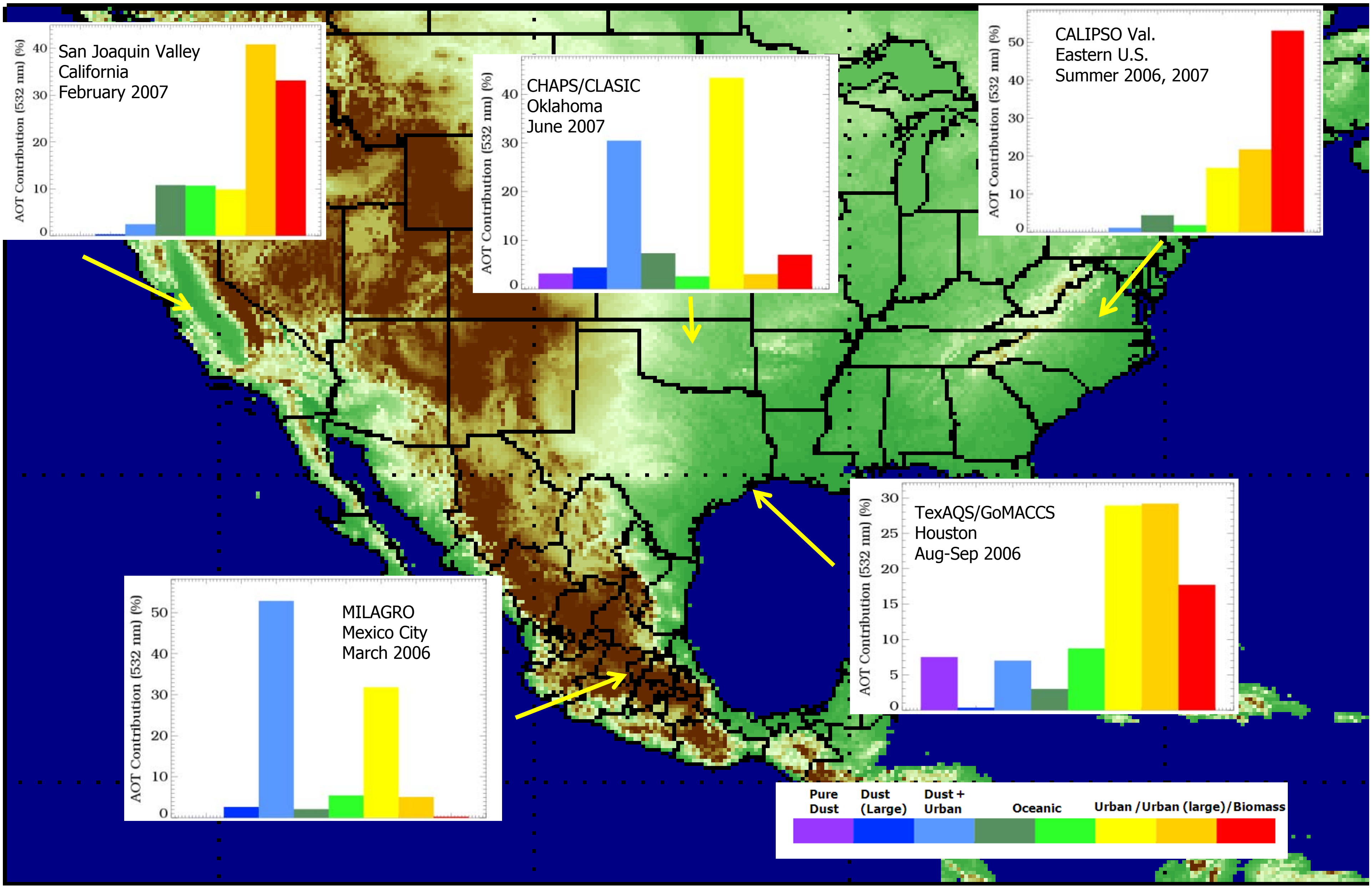
HSRL – more accurate information on aerosol extinction, optical depth, and type



1 pure dust
2 dust (large)
3 dust (small)+urban
4 oceanic
5 urban/industrial (small)+biomass
6 SE Asia+urban+biomass
7 biomass+urban+SE Asia



Aerosol Optical Thickness Apportionment by Type



Multiwavelength HSRL

- ***3β+2α*** HSRL
  - Backscatter at 3 wavelengths (***3β***) : 355, 532, 1064 nm
  - Extinction at 2 wavelengths (***2α***) : 355, 532 nm
  - Depolarization at 355, 532, and 1064 (dust and contrails/cirrus applications)

- Retrieved, layer-resolved, aerosol microphysical and macrophysical parameters (Müller et al., 1999, 2000, 2001; Veselovskii et al.,2002,2004)
  - Effective and mean particle radius (errors < 30-50%)
  - Concentration (number, volume, surface) (errors < 50%)
  - Complex index of refraction
    - real (±0.05 to 0.1)
    - imaginary (order of magnitude if < 0.01; <50% if > 0.01)
  - Single scatter albedo (±0.05)

Multiwavelength HSRL

- Downside of *$3\beta+2\alpha$* retrieval
  - Assumes wavelength-independent refractive index
  - Currently works only for spherical particles (upgrade to spheroids planned)
  - Currently time consuming and requires expert operator (however, Europeans are adopting and automating retrieval for their ground-based Raman lidar network)

- However, the technique has been validated against in situ measurements and is the only known technique of any kind for vertically resolved microphysical retrievals.

Multi-Wavelength HSRL Issues

- HSRL much more complex than backscatter lidar
- Multi-wavelength HSRL never been demonstrated
  - Component technologies have been demonstrated
  - Several institutions are working on instrument demonstrations
    - LaRC expects to demonstrate an airborne system in 2009
  - Retrievals demonstrated via Raman lidar measurements
- Higher risk laser
  - Lifetime at 355 nm has not been demonstrated (ADM and EarthCare missions will demonstrate)
- Multi-wavelength HSRL requires higher power-aperture product
  - More power required for laser
  - More volume/mass for the telescope

Progression of Aerosol Lidar Capability

Backscatter Lidar
(GLAS, CALIPSO)

Backscatter Lidar + Passive
(CALIPSO + A Train)

3β+2α Advanced HSRL

- Aerosol layer heights
- Vertical distribution (total attenuated backscatter)
- Aerosol type vs. altitude
- Extinction, backscatter retrieval via assumed optical properties
- Extinction via column constraint
- Fine-coarse mode fraction vs. altitude
- Extinction profile
- Complex refractive index vs. altitude
- Aerosol size vs. altitude
- SSA vs. altitude
- Concentration vs. altitude

(Kaufman et al., 2003;
Léon et al., 2003)

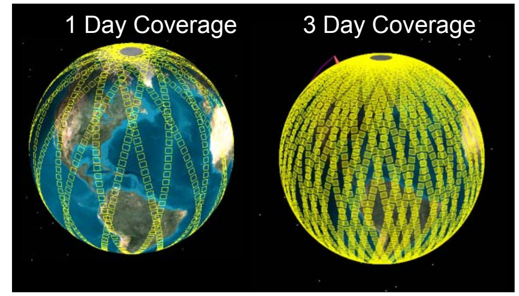
Further enhanced by addition of passive sensors (e.g. multiangle polarimeter)

Combined Active-Passive Retrievals

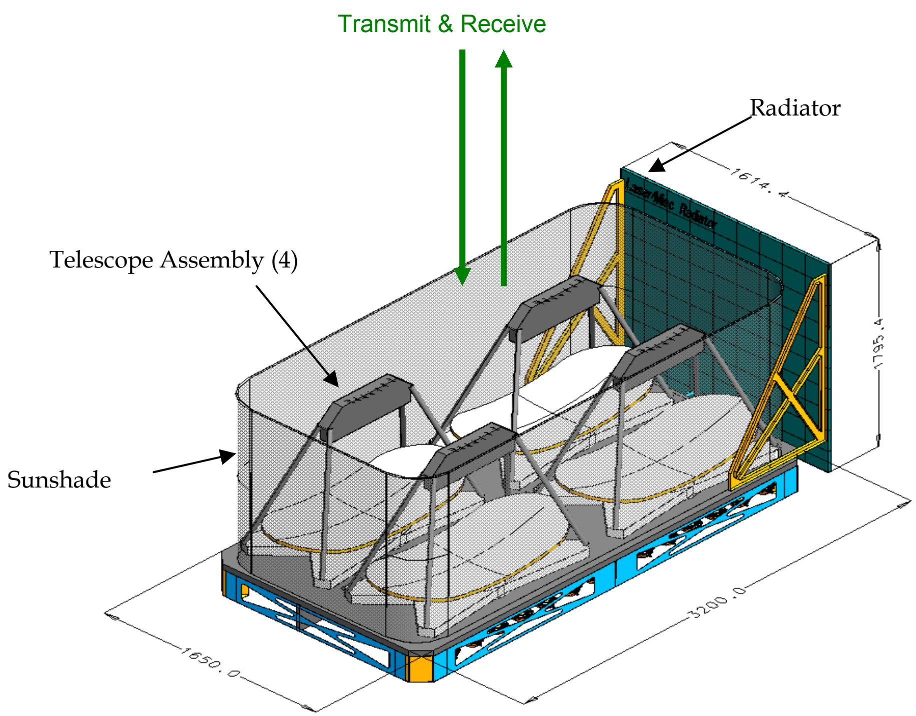
- Anticipate that ACE lidar data will be used in **combined lidar-polarimeter retrieval**
  - Reduce reliance on limiting assumptions of lidar techniques
  - Increase vertical and horizontal resolution at which type and microphysical information can be retrieved
  - Increase accuracy of profile products
  - Increase number of parameters that can be retrieved

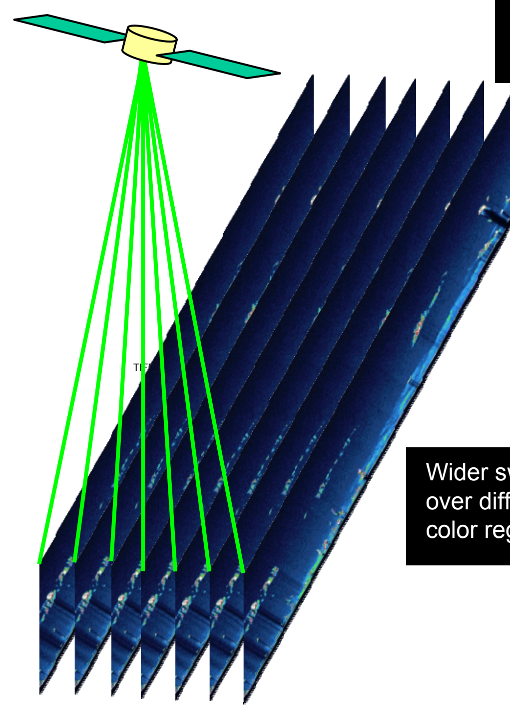
Multi-Beam Lidar Concept from Previous ACE Mission Study

- **Two-wavelength (532, 1064 nm), polarization-sensitive**
- **Wider swath for better global coverage:**
  - **Multiple beams increase number of statistical-based mission observations**
  - **Enables better aerosol emission/source identification**
  - **Improved ability to track plumes during long-range transport**
  - **Combined lidar and imager observations (e.g. ocean biology)**
- **Beam spacing fine enough to resolve aerosol structure across most plumes, near sources, and for downwind advection**



Improved spatial coverage through complicated aerosol plumes





Wider swath profiling over difficult ocean color regions

Backups and Leftovers

HSRL: 2 equations, 2 unknowns

Measured Signal on Molecular Scatter (MS) Channel:

$$P_{MS}(r) = \frac{C_{MS}}{r^2} F(r)\,\beta_m(r)\,\exp\left\{-2\int_0^r \left[\sigma_m(r') + \underline{\sigma_p(r')}\right] dr'\right\}$$

Particulate Extinction

Measured Signal on Total Scatter (TS) Channel:

$$P_{TS}(r) = \frac{C_{TS}}{r^2}\left[\beta_m(r) + \underline{\beta_p(r)}\right]\exp\left\{-2\int_0^r \left[\sigma_m(r') + \sigma_p(r')\right] dr'\right\}$$

$$\frac{\sigma_p(r)}{\beta_p(r)} = \underline{S_p}$$

Ext/Backscatter

Particulate Backscatter

Retrieved Parameters

High Spectral Resolution Lidar (HSRL)

- The HSRL technique offers significant advantages over the standard backscatter lidar.
  - The HSRL technique enables independent retrieval of aerosol backscatter and extinction without assumption of the lidar ratio.
    - Greater accuracy in Level-2 extinction and backscatter products
    - Higher information content due to independence of extinction and backscatter. Lidar ratio is an added intensive observable that can be used to better infer aerosol type
  - The HSRL technique can be internally calibrated
    - Does not rely on assumption of aerosol backscatter at some calibration altitude
    - Internal calibration possible over entire orbit, day or night

- The disadvantage to HSRL is greater complexity and higher power-aperture product

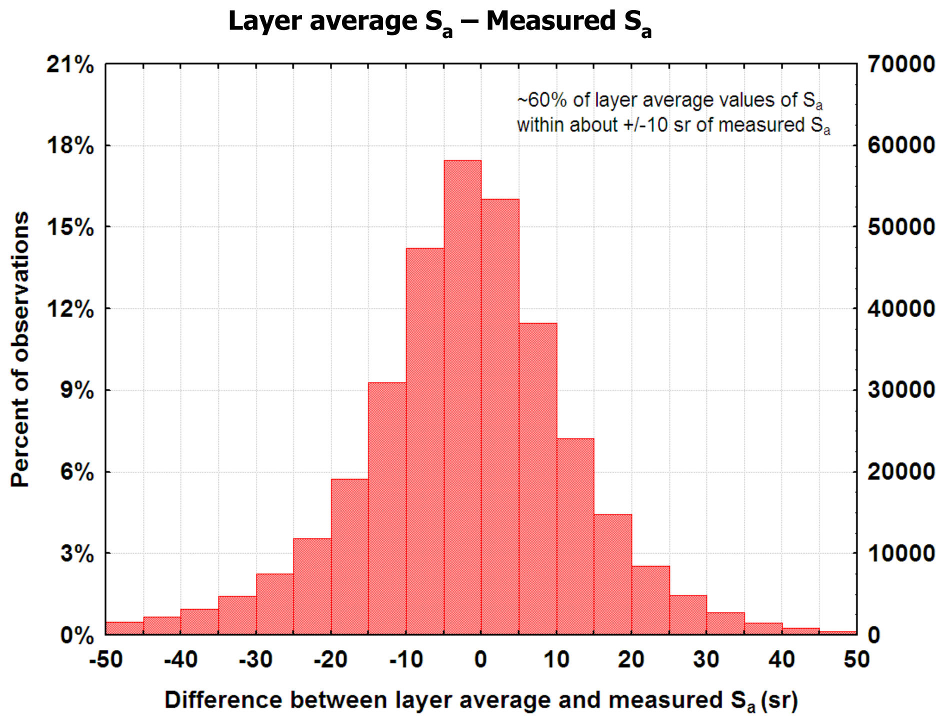
Multi-Wavelength HSRL Issues

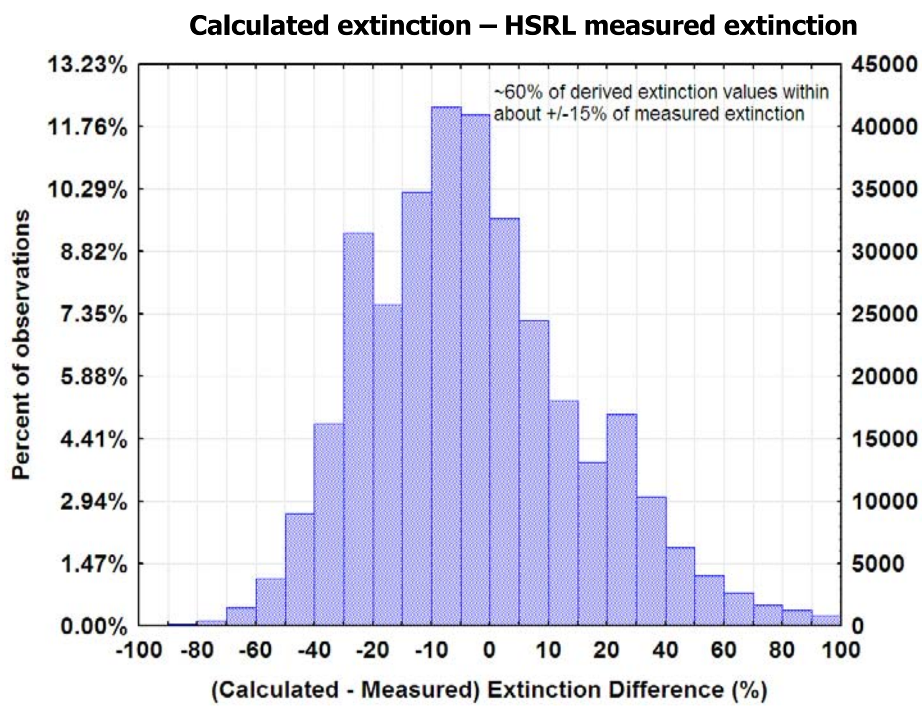
- Pros
  - Can be internally calibrated, day or night
  - More straightforward retrievals
  - More accurate extinction and backscatter (no assumptions)
  - Higher information content for aerosol typing
  - Only method for altitude-resolved microphysical retrievals

- Cons
  - HSRL much more complex than backscatter lidar
  - Multi-wavelength HSRL never been demonstrated
    - Technologies have been demonstrated
    - Several institutions are working on instrument demonstrations
      - LaRC expects to demonstrate an airborne system in 2009
  - Multi-wavelength HSRL requires higher power-aperture product
    - More power required for laser
    - More volume/mass for the telescope

Error in S_a and Extinction Using Constrained Retrieval

Vertical variability of the lidar ratio is examined using HSRL data acquired during field campaigns from 2006 and 2007

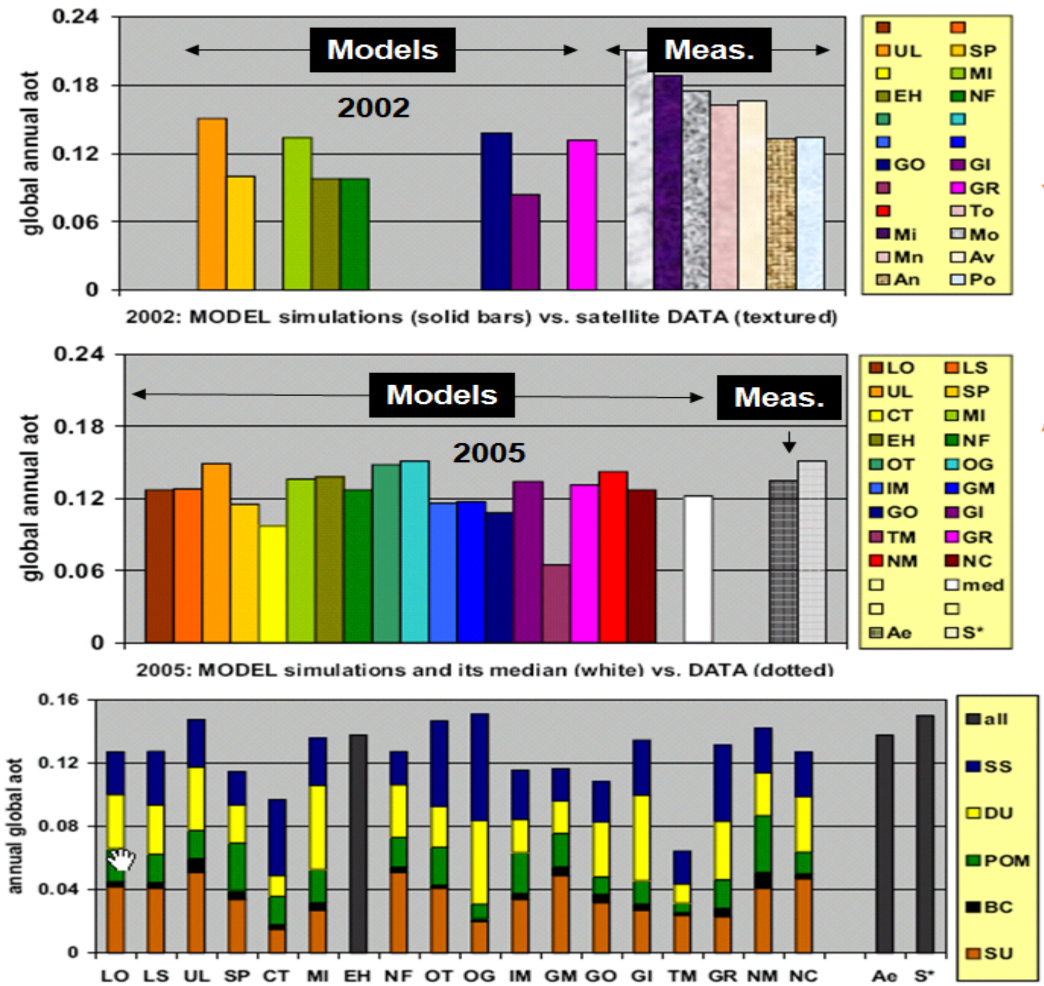




- S_a is relatively constant about 60% of the time over the 0-6 km layer
- Aerosol extinction derived using HSRL backscatter and the layer AOT constraint is within +/15% of the aerosol extinction derived directly using the HSRL technique about 60% of the time

Problem Area – Model Aerosol Composition Varies Widely

- ~~Extensive satellite AOT measurements help reduce variability among global~~ model AOT simulations
- Large differences among model simulations of aerosol composition



Global

Model representations of global annual AOT have become closer to observations between 2002 to 2005

But…

Large model differences compositional mixture

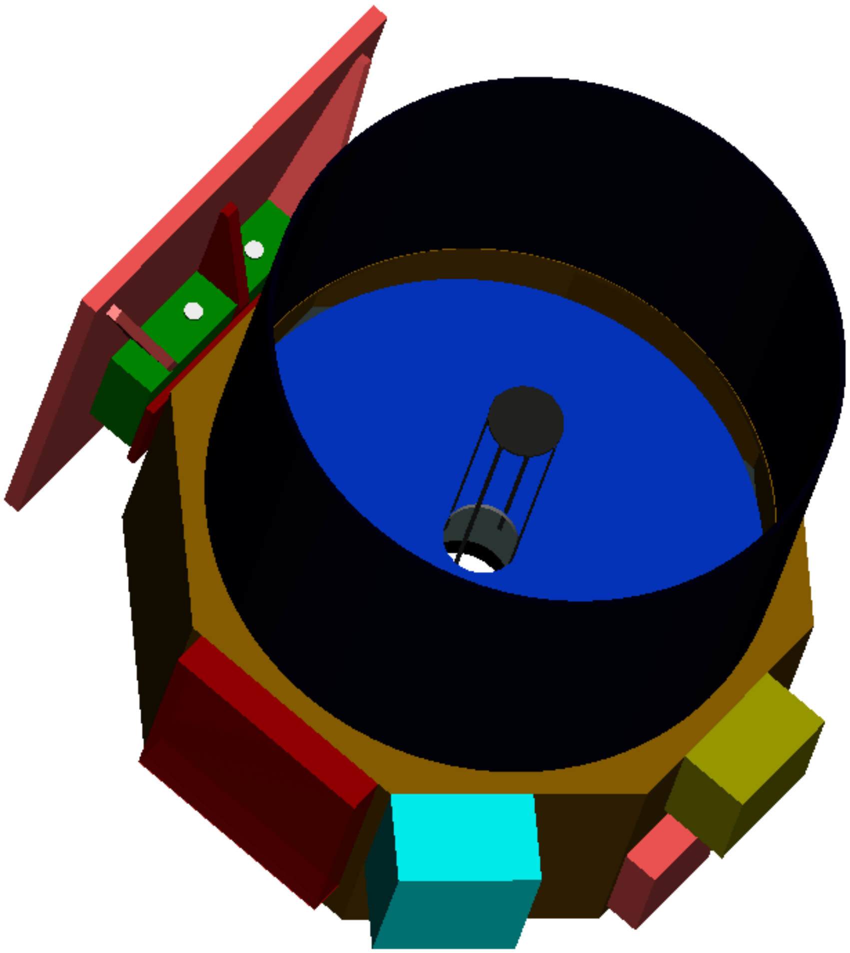
Kinne et al., 2005

Past ACE Lidar Considerations

- Science Working Group convened by HQ in January 2007 to flesh out ACE mission concept
  - Better define science objectives/requirements
  - Mission concept design and cost estimate

- 2 lidar concepts considered to Science Working Group
  - GSFC multi-beam backscatter lidar
  - LaRC multi-wavelength HSRL

Multiwavelength HSRL Concept from Previous ACE mission study

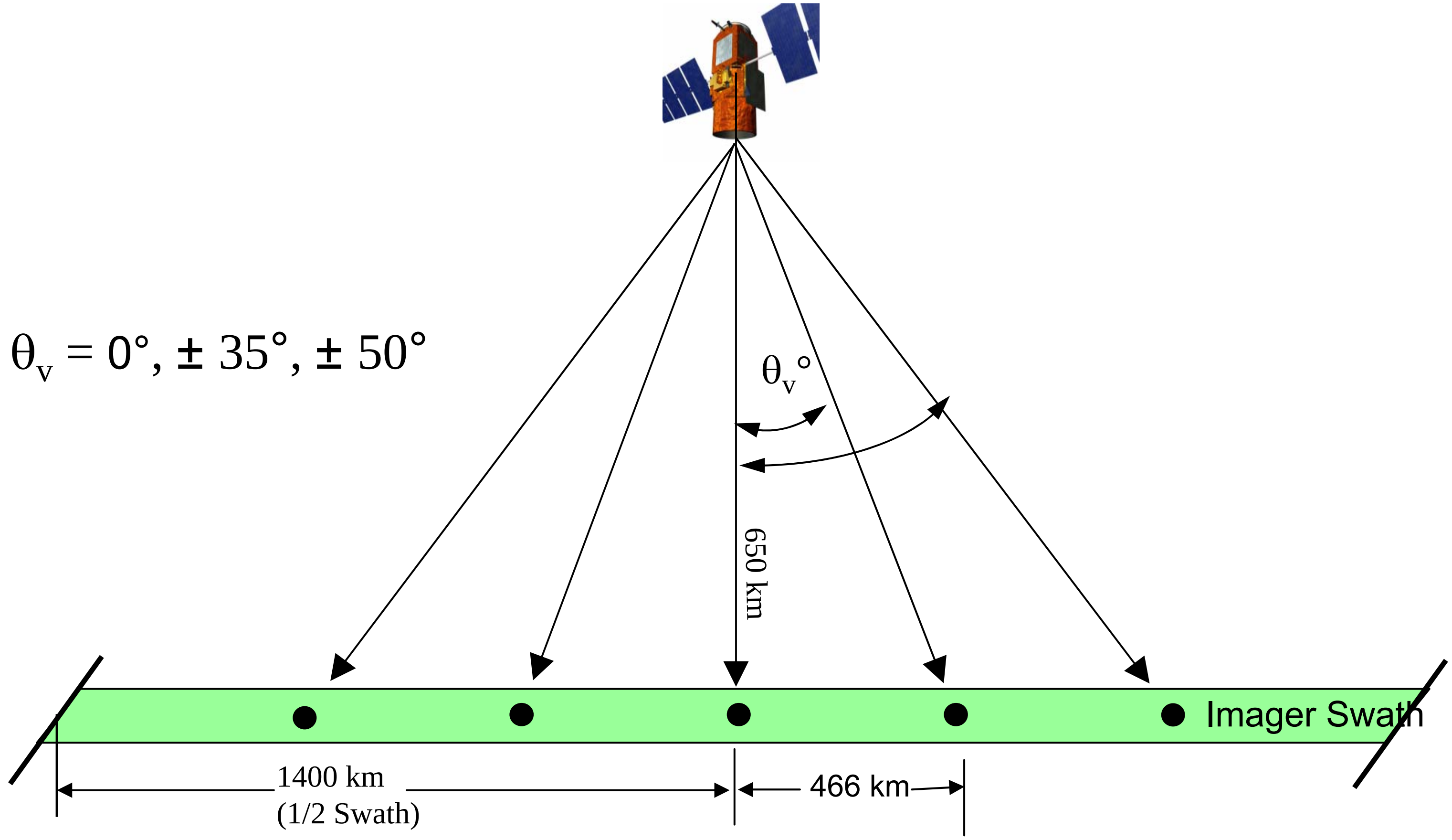


- Measurements
  - Backscatter at 355, 532, 1064 nm
  - Extinction 355 and 532 nm
  - Depolarization 355, 532, 1064 nm
  - Ocean subsurface at 532 nm
  - Vegetation canopy at 1064 nm

- Instrument summary
  - Transmitter:
    - 25 W avg. output power
    - 2 lasers (1 redundant)
  - Telescope: 1.5-m diameter

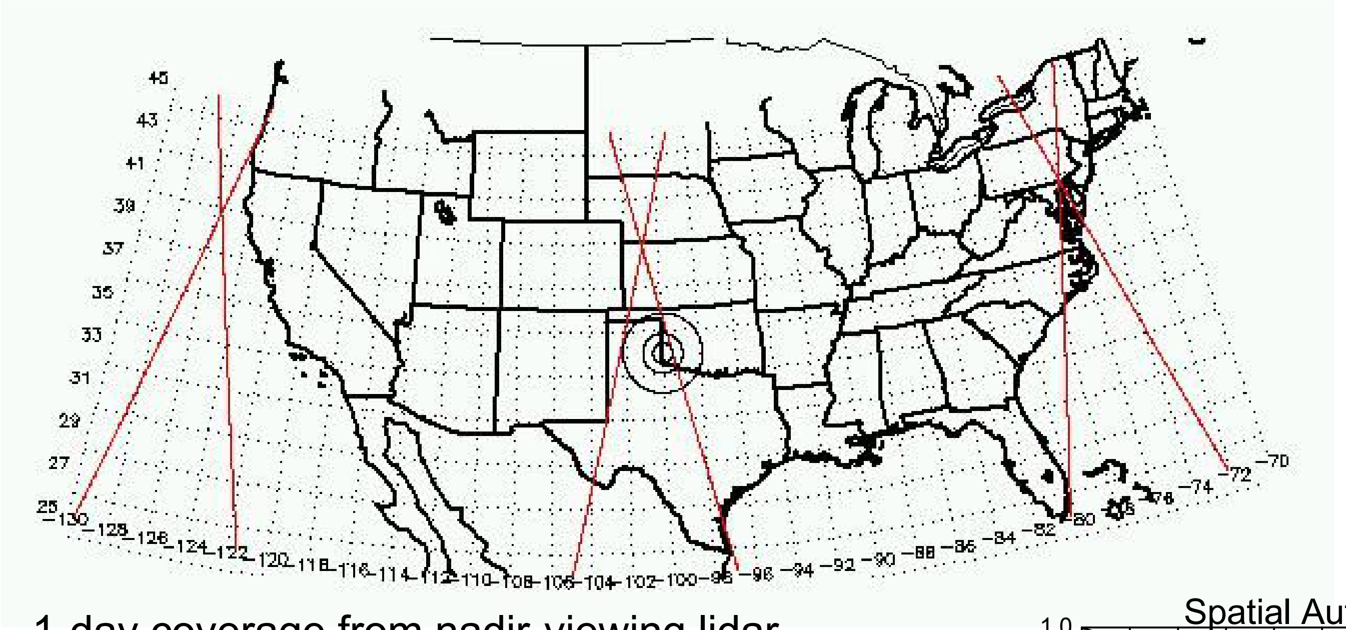
- Single nadir beam, but higher information content for
  - Lidar + polarimeter retrievals of aerosol optical and microphysical parameters
  - Lidar + radar cloud retrievals

Not considered in past study: Multi-Beam Lidar with Wider Field of Regard

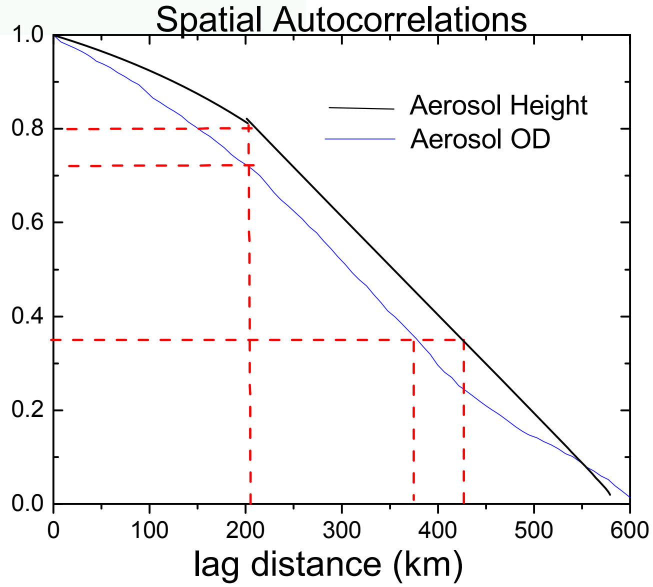


- Beams spaced by 466 km using multiple apertures, span most of ORCA swath, provide 1-day "coverage" of the US
- Central 3 beams span half of ORCA swath, provide 2-day US coverage

Spatial sampling from nadir-viewing lidar



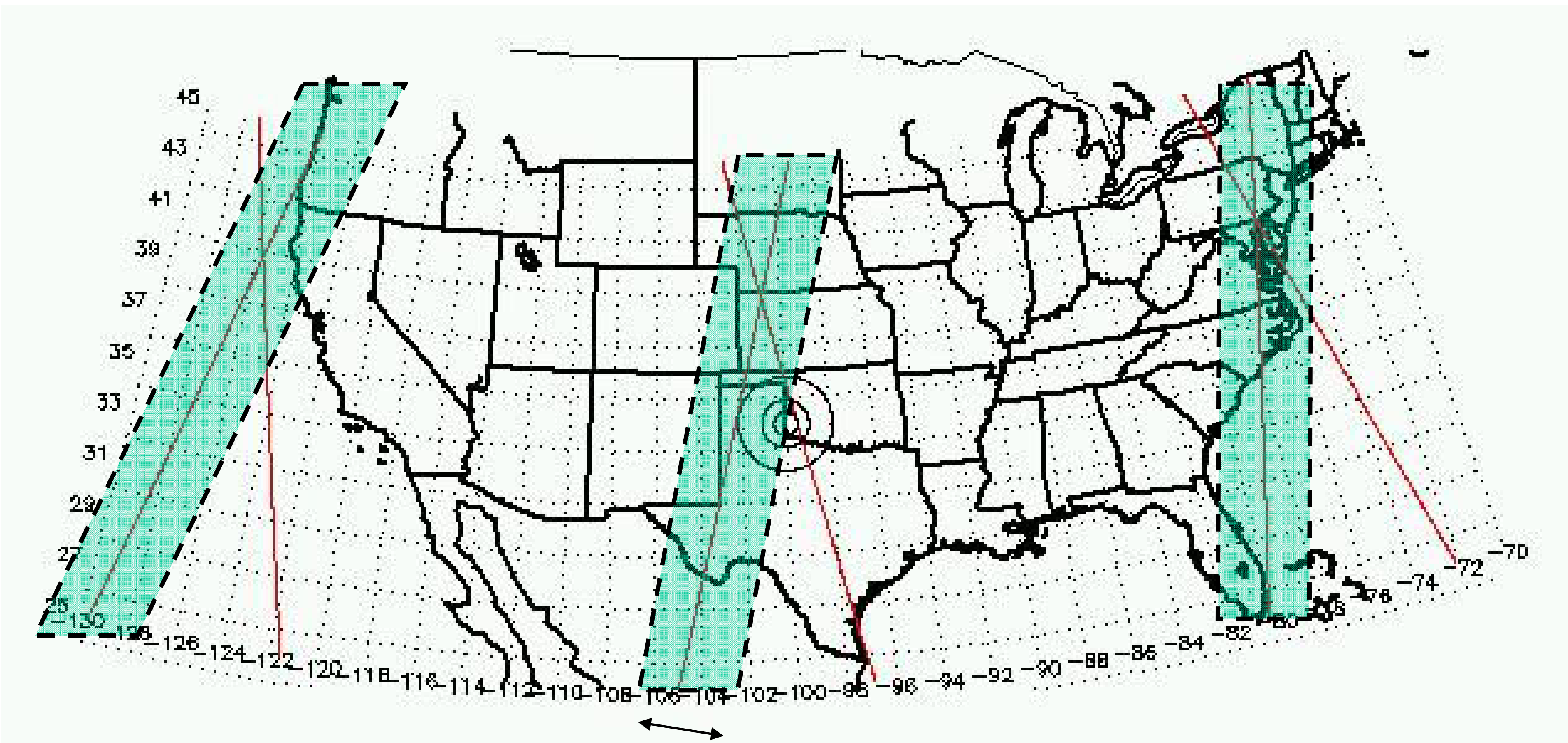
1-day coverage from nadir-viewing lidar



- Along-track statistics from LITE show aerosol spatial correlations drop to less than 0.8 at 200 km
- The nadir view explains only about 50% of aerosol variability 200 km away
- Aerosol field is essentially uncorrelated beyond 400 km

Spatial sampling from nadir-viewing lidar

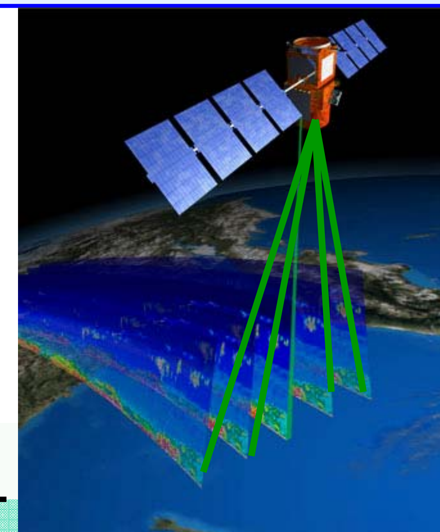
Effective horizontal area over which single nadir beam provides information on vertical structure of aerosol for one day.

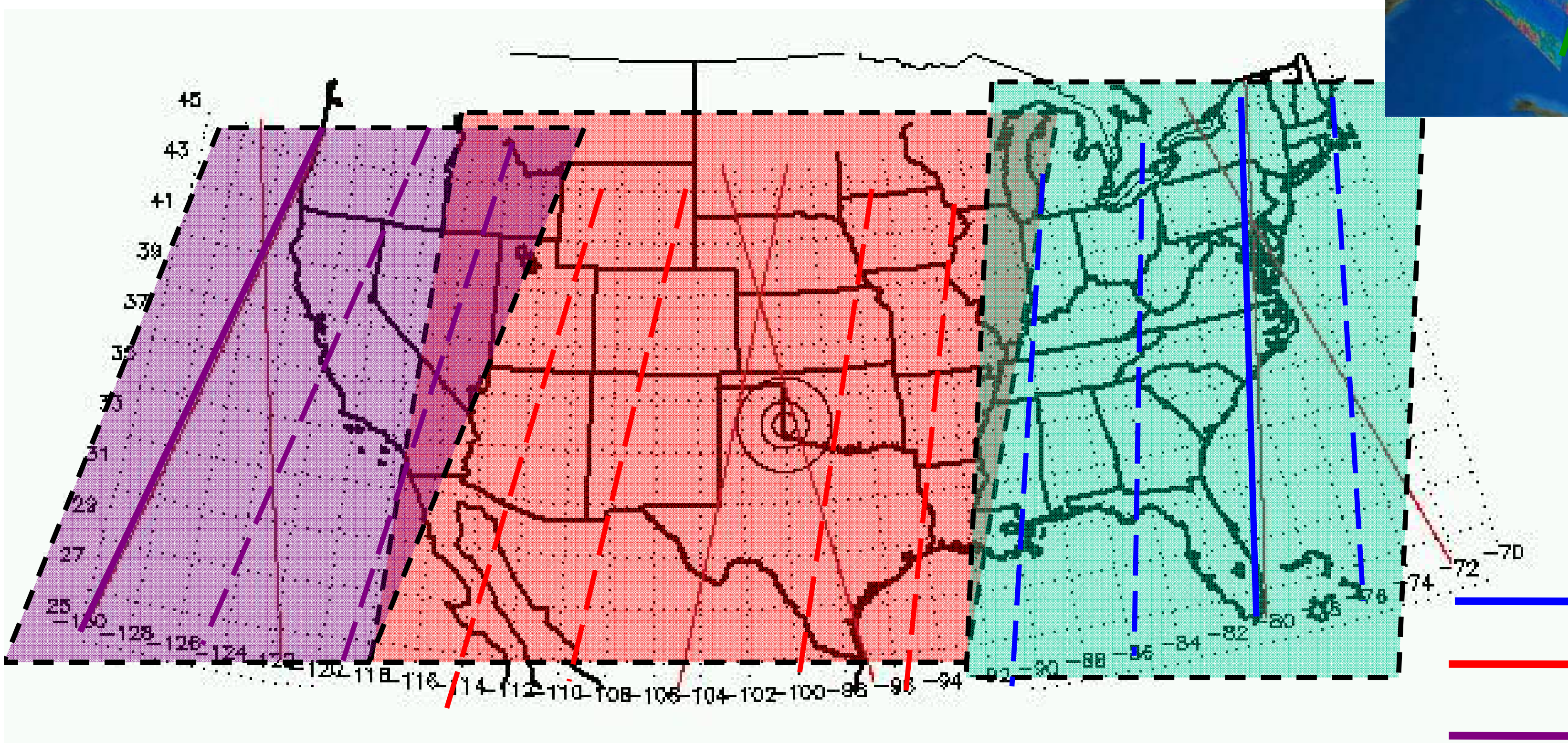


2 x 200 km

One-Day Coverage with Wide Field of Regard Multi-Beam Lidar

- Goal is to get increased coverage to
  - Improve statistics on clouds and aerosols (more samples)
  - Provide better coverage to correct aerosol error in ocean color imager
  - Provide data for operational air quality forecast models





1:30 EST

3:09 EST

4:48 EST

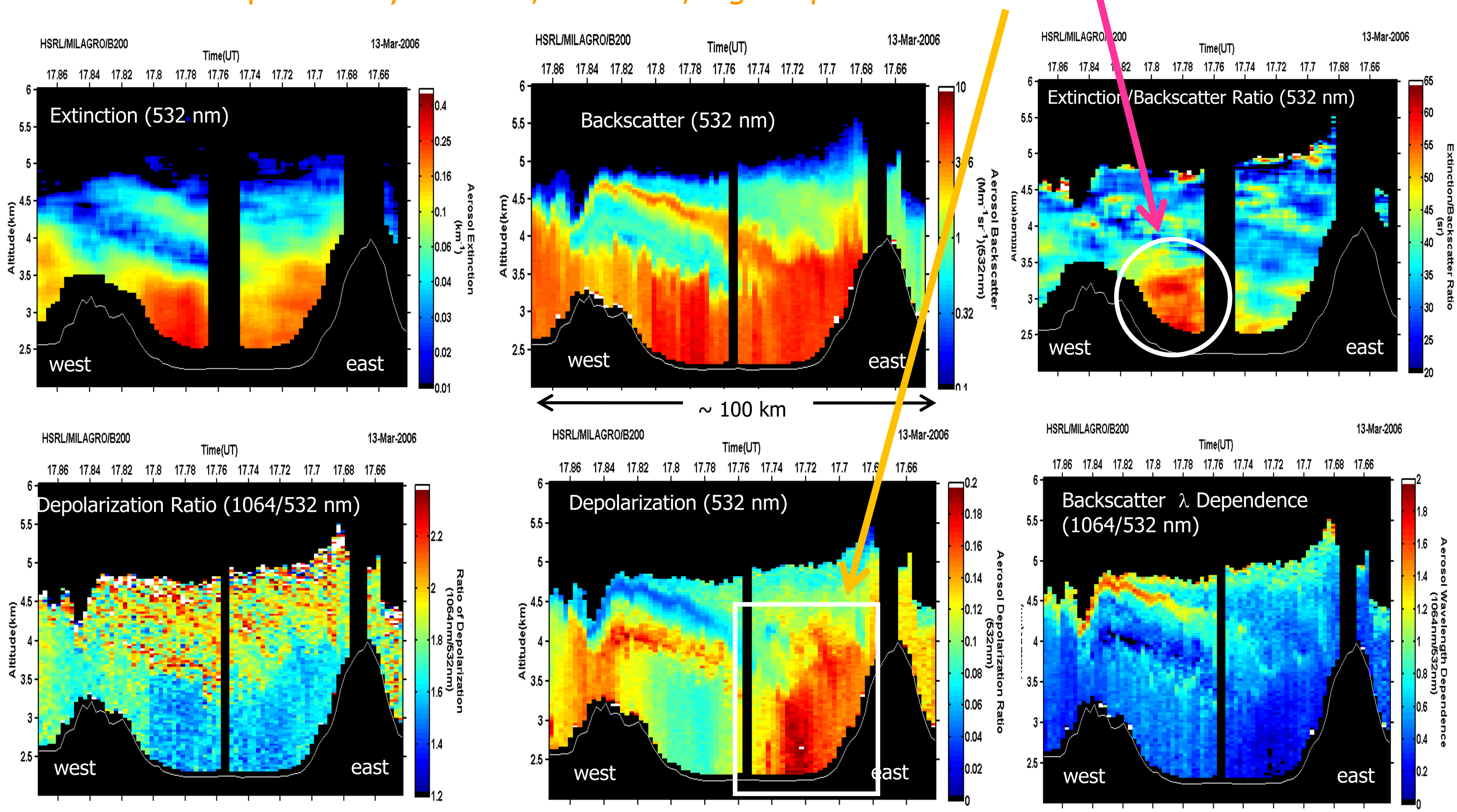
Basic Lidar Data Products: Extensive vs. Intensive

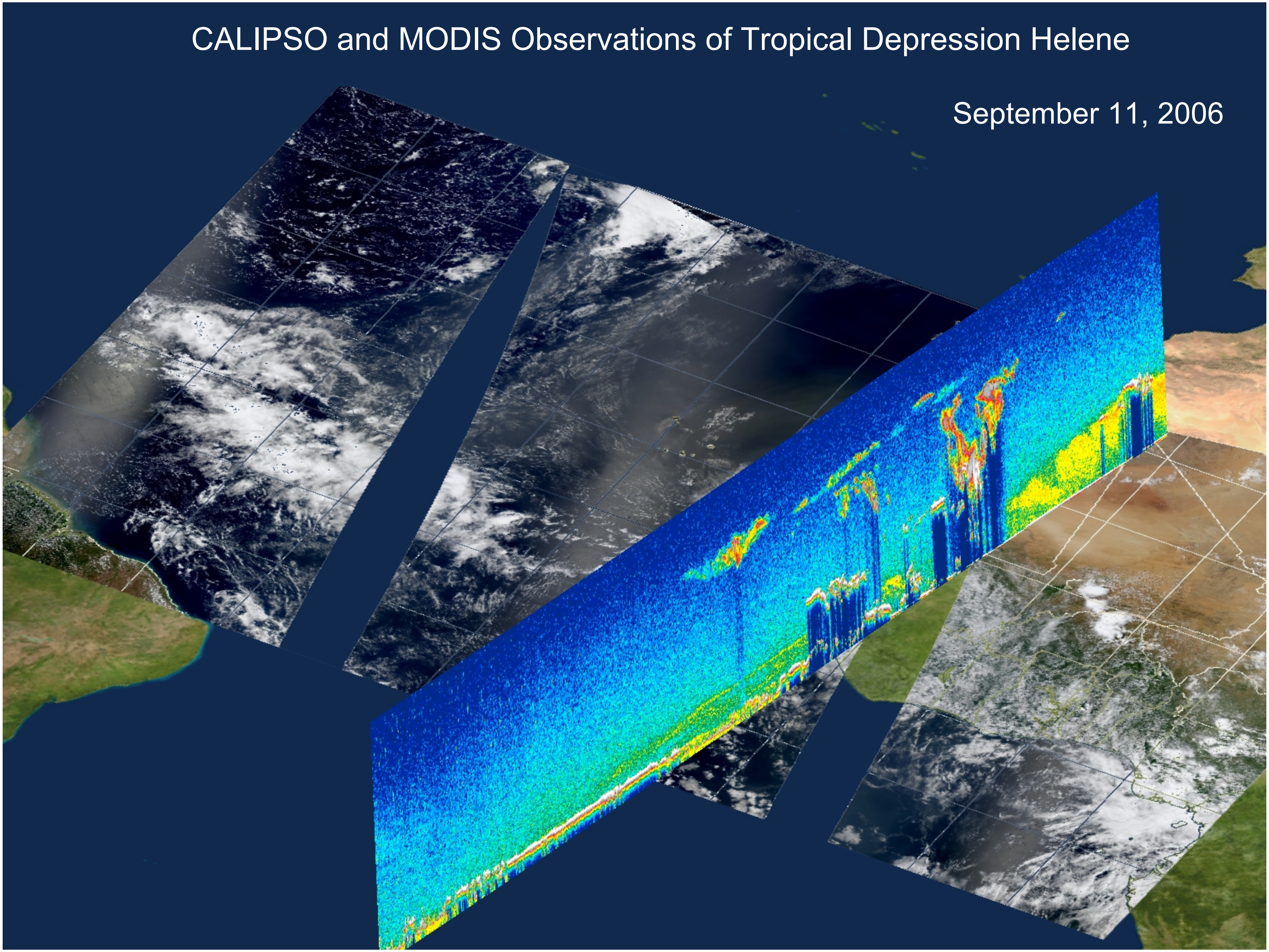
- **Extensive products:** depend upon aerosol amount and type
  - Attenuated backscatter profile
  - Aerosol backscatter profile
  - Aerosol extinction profile
  - Aerosol optical depth
  - Total depolarization ratio
- **Intensive products:** independent of aerosol amount; depend only on aerosol type (composition), shape, and size
  - Aerosol depolarization ratio
  - Aerosol backscatter wavelength dependence (Angstrom coefficient for backscatter

HSRL – more accurate information on aerosol extinction, optical depth, and type

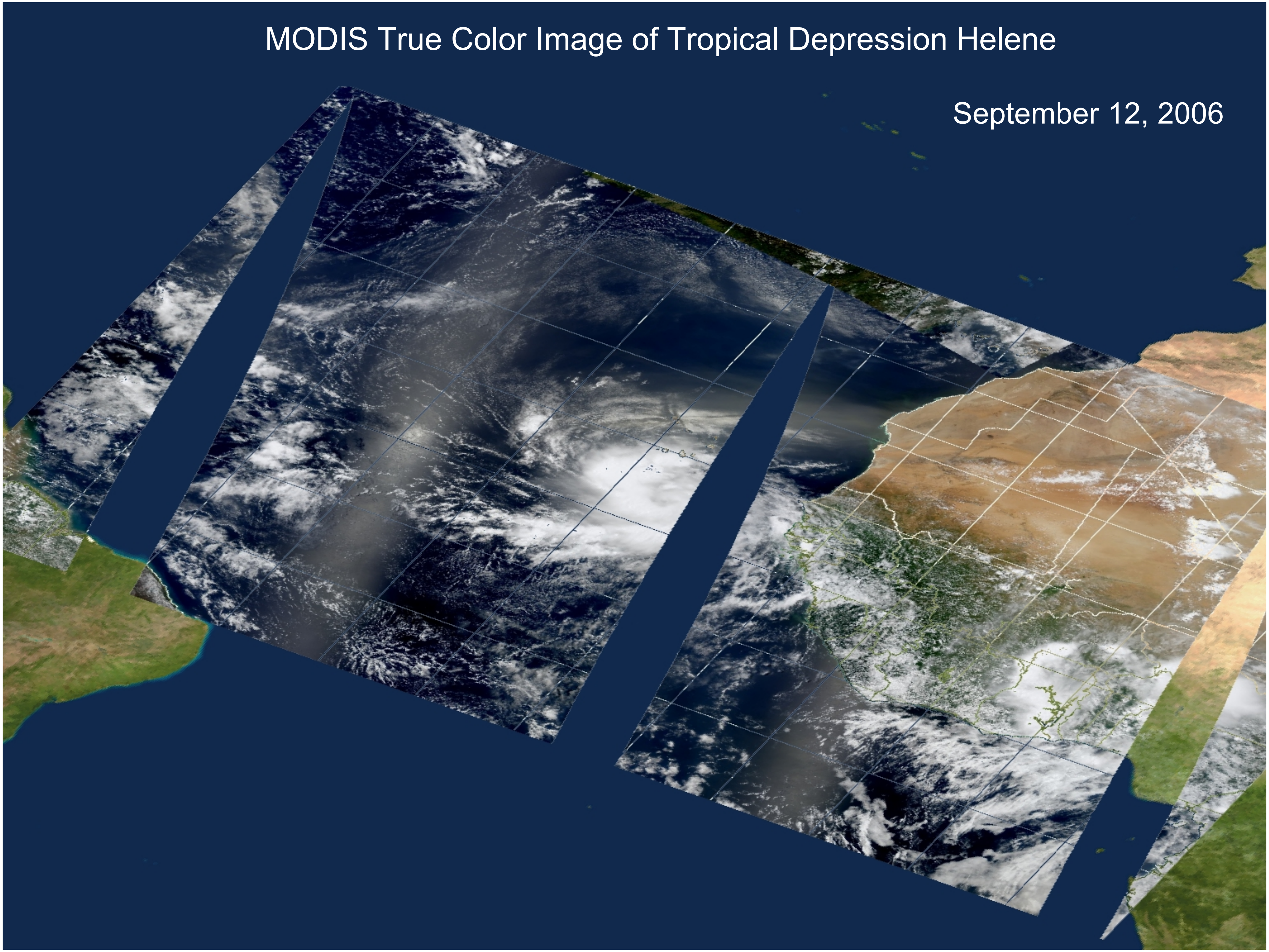
LaRC Airborne HSRL Measurements over Mexico City, March 13, 2006

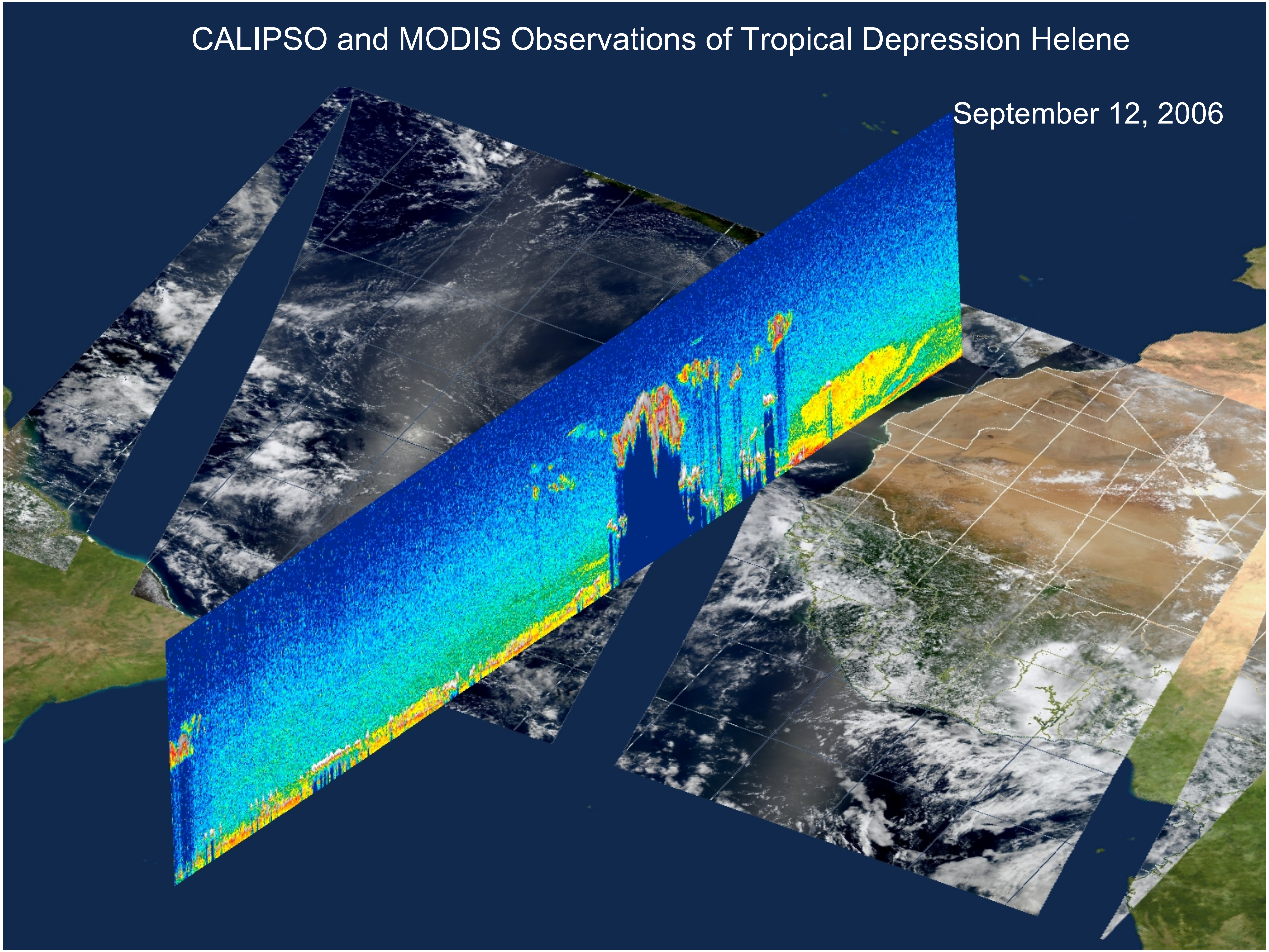
- western part of city- high S_a, high WVD, low depolarization – urban aerosol
- eastern part of city - low Sa, low WVD, high depolarization – dust

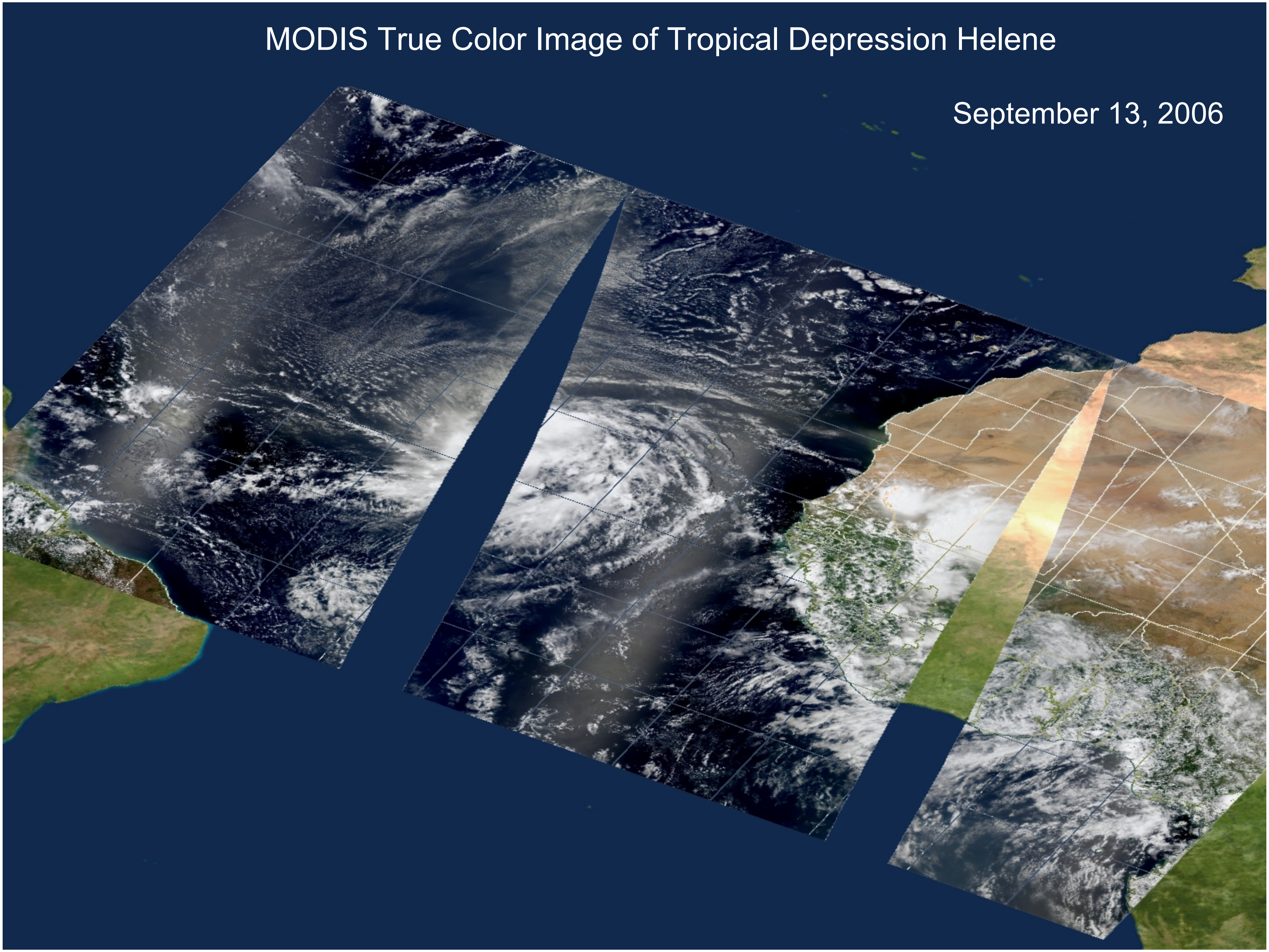


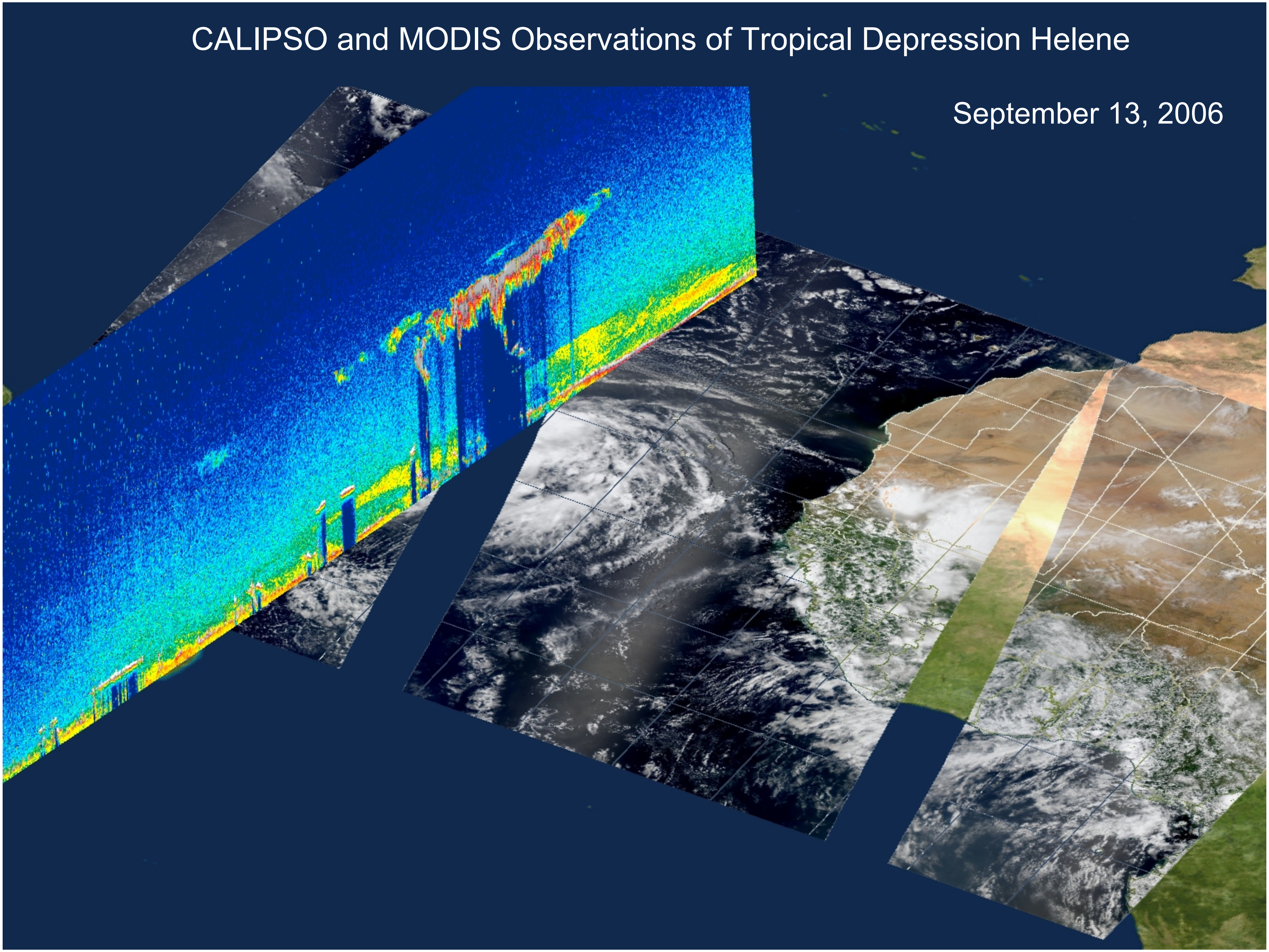

CALIPSO and MODIS Observations of Tropical Depression Helene
September 11, 2006

MODIS True Color Image of Tropical Depression Helene



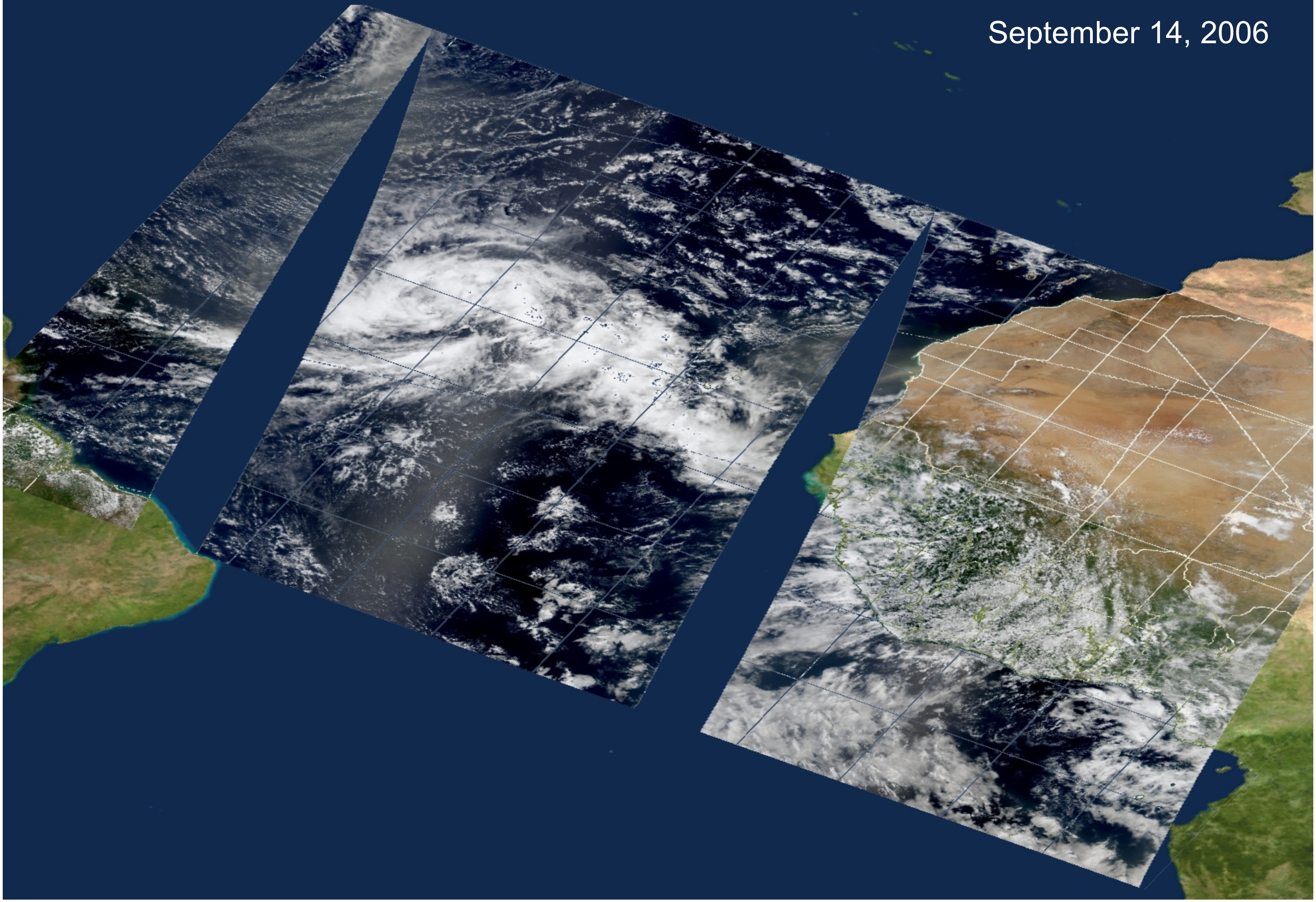

CALIPSO and MODIS Observations of Tropical Depression Helene
September 12, 2006

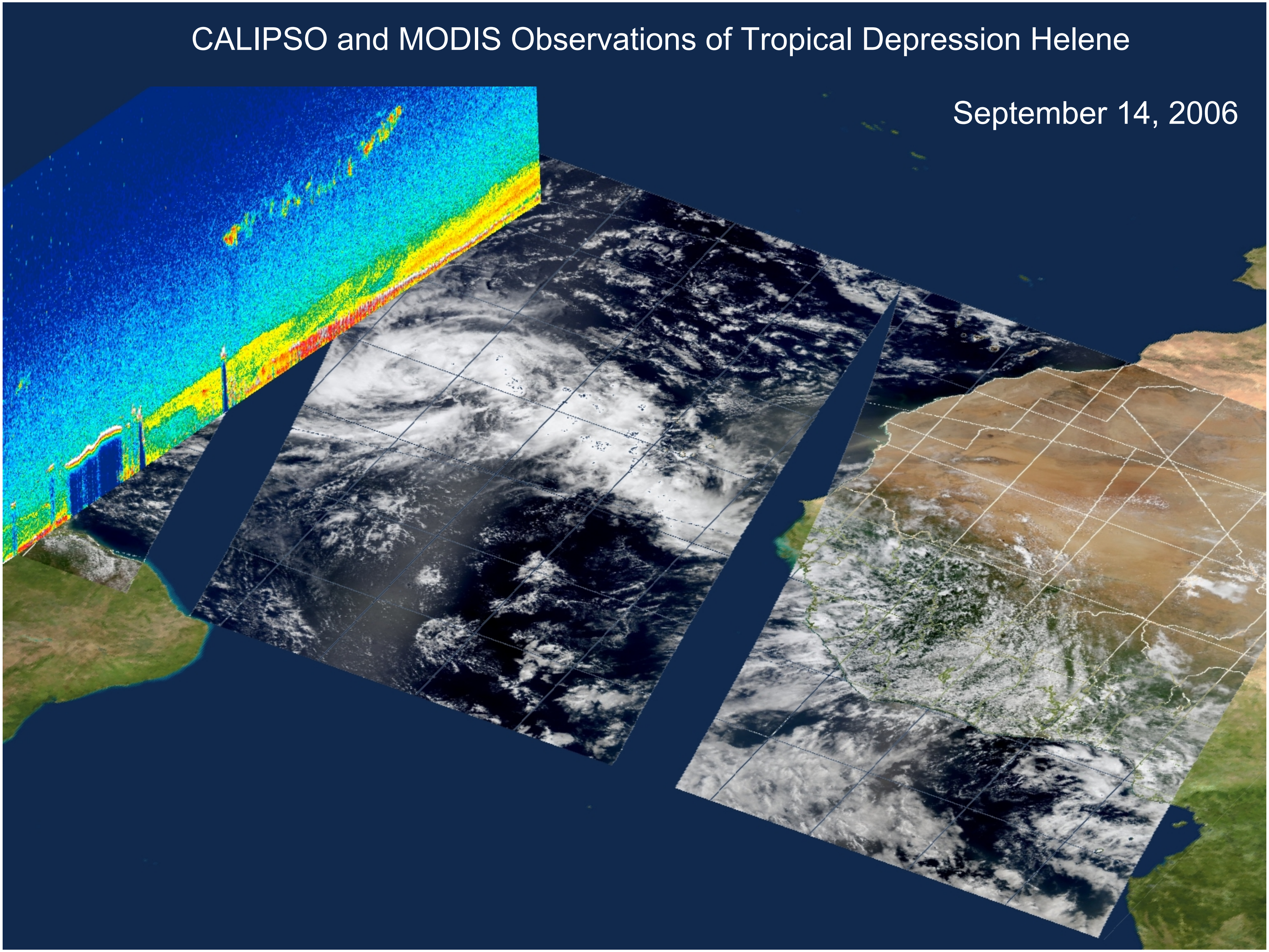

MODIS True Color Image of Tropical Depression Helene
September 13, 2006


CALIPSO and MODIS Observations of Tropical Depression Helene
September 13, 2006

MODIS True Color Image of Tropical Depression Helene

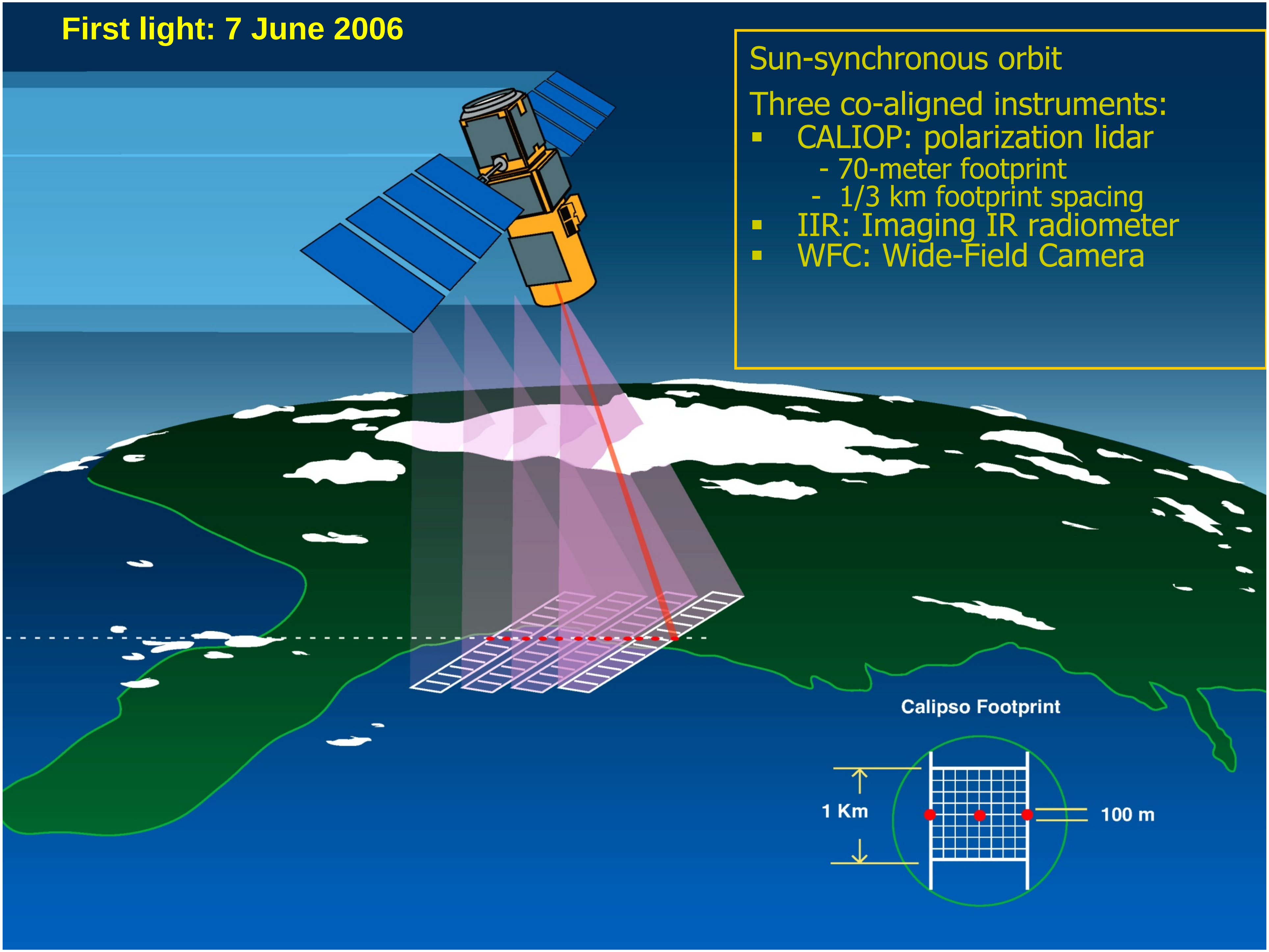
September 14, 2006




CALIPSO and MODIS Observations of Tropical Depression Helene
September 14, 2006

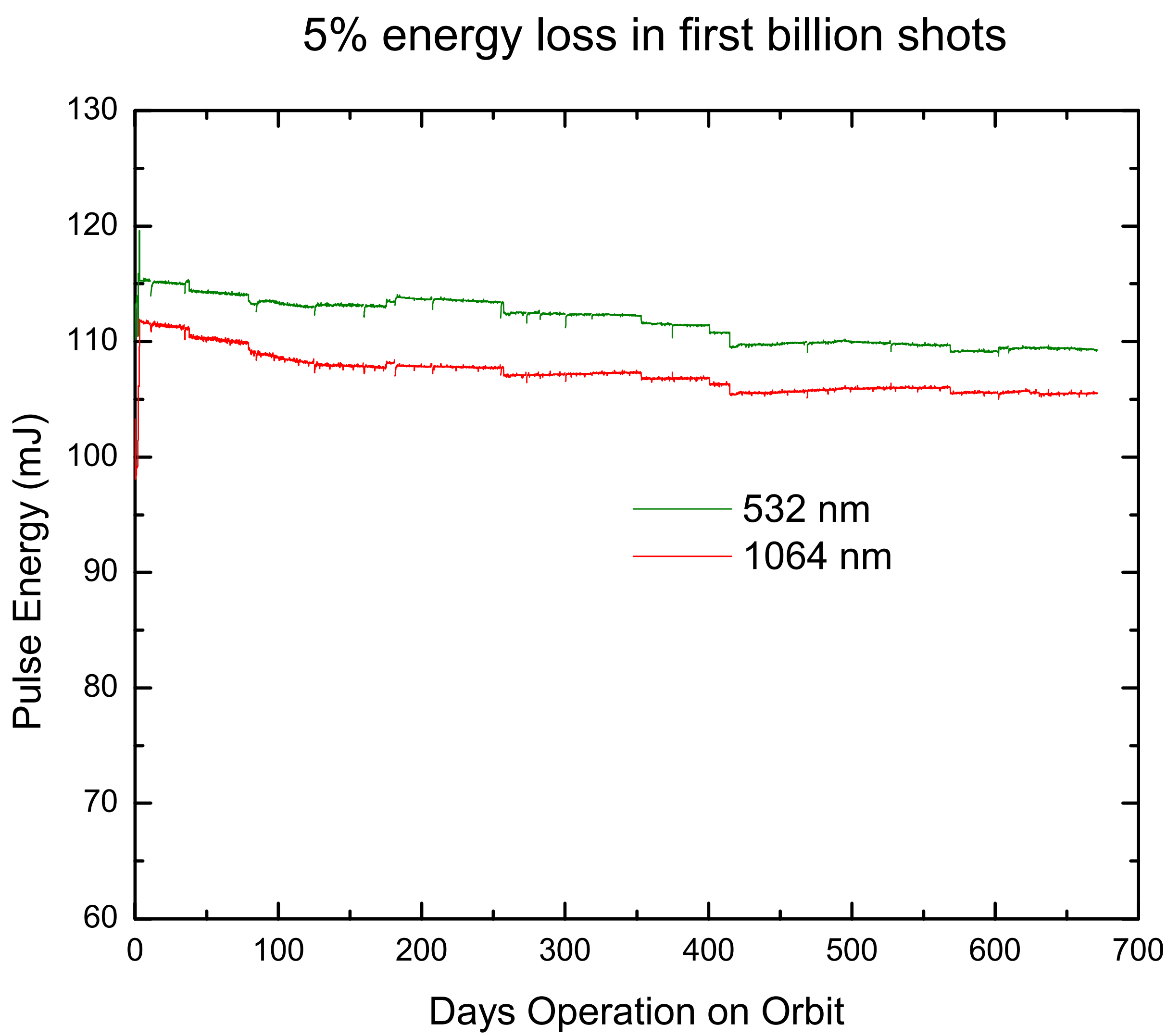
Cloud and Aerosol from CALIPSO

Dave Winker
NASA Langley, Hampton, VA



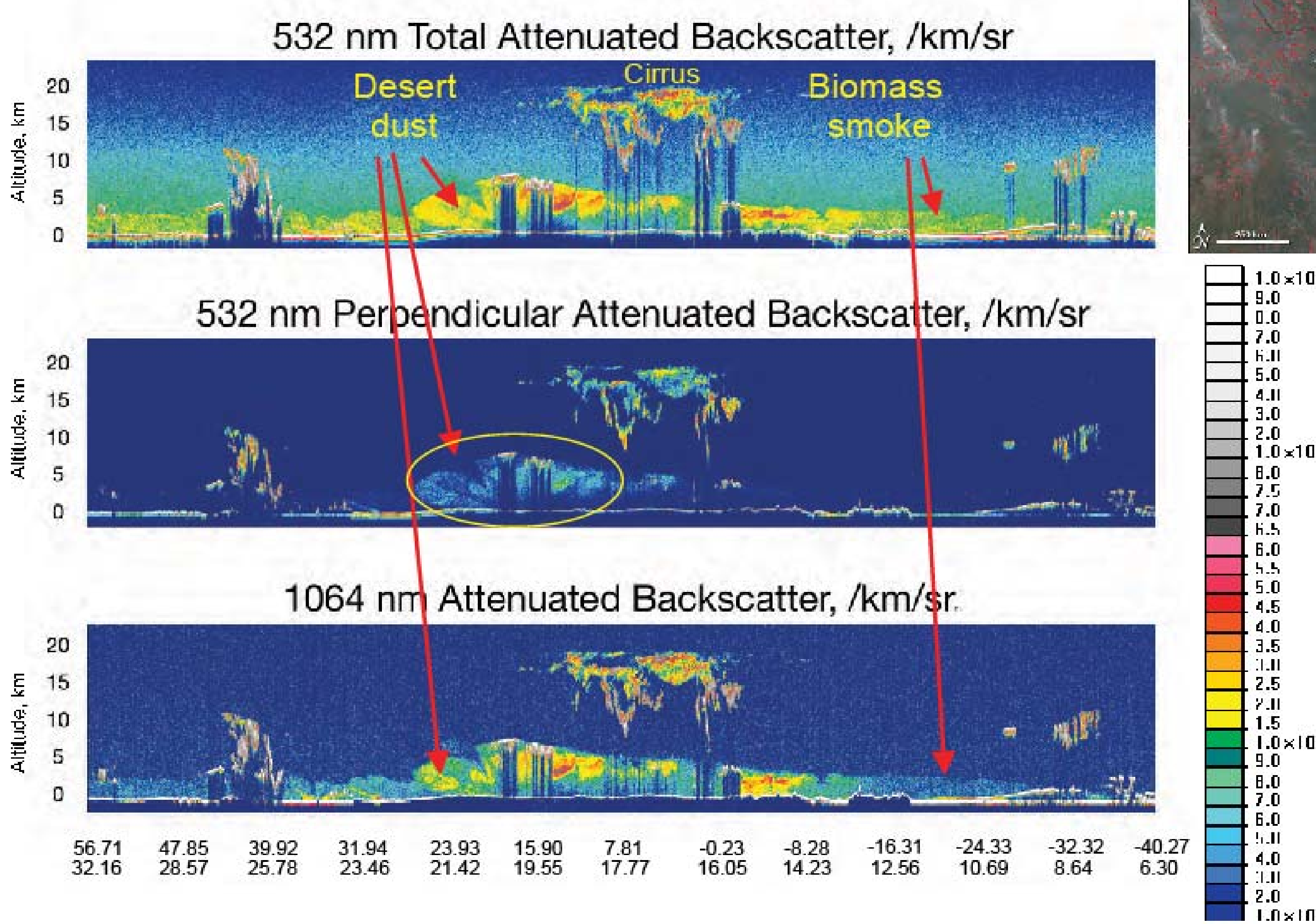
First light: 7 June 2006
Sun-synchronous orbit
Three co-aligned instruments:
▪ CALIOP: polarization lidar
- 70-meter footprint
- 1/3 km footprint spacing
▪ IIR: Imaging IR radiometer
▪ WFC: Wide-Field Camera
Calipso Footprint
1 Km
100 m

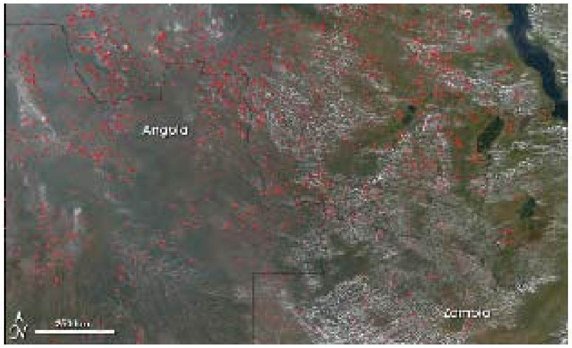
Laser Energy Trend through May 2008 (~1.2 billion shots)



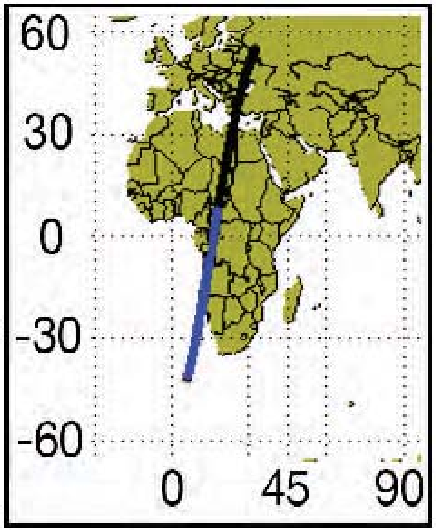
CALIOP First Light Observations
(all 3 channels)

June 9, 2006

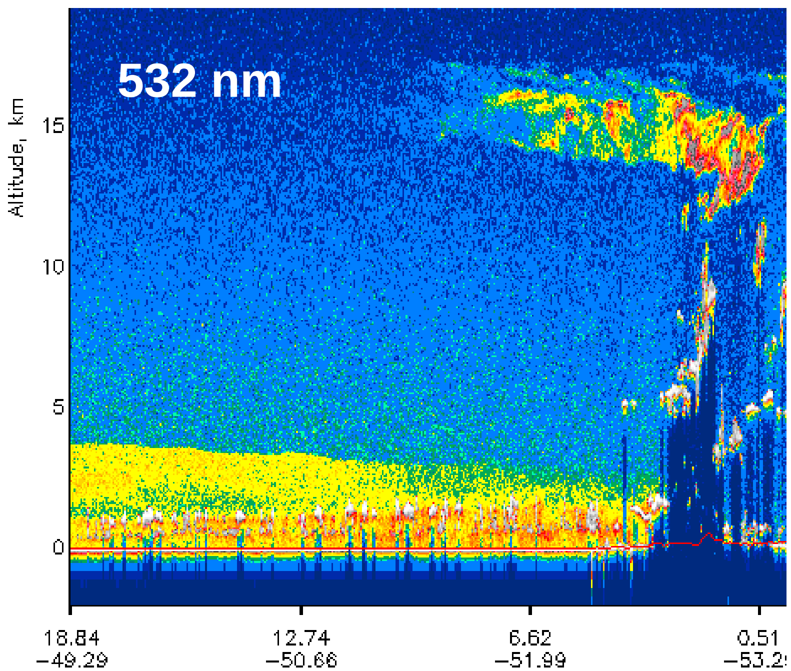


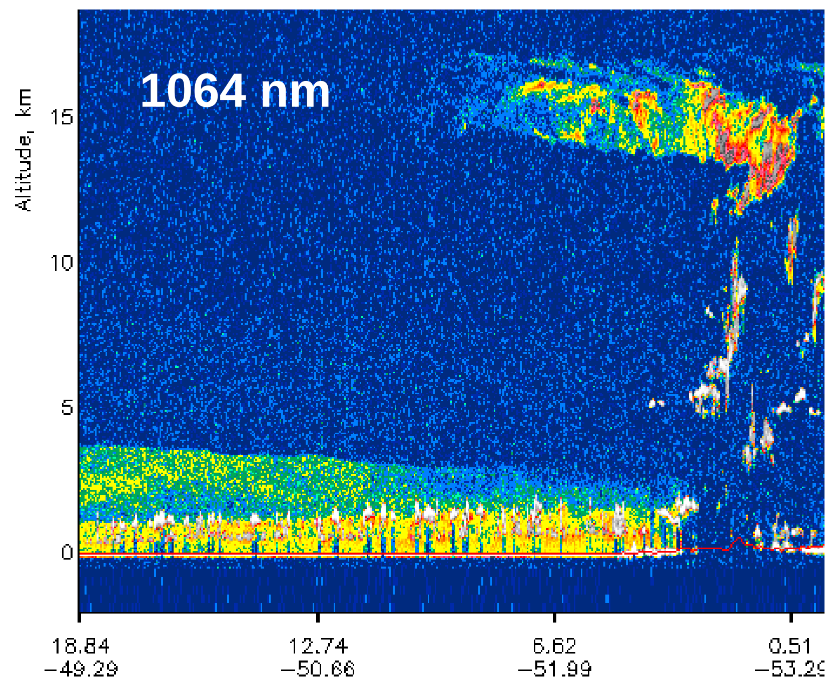


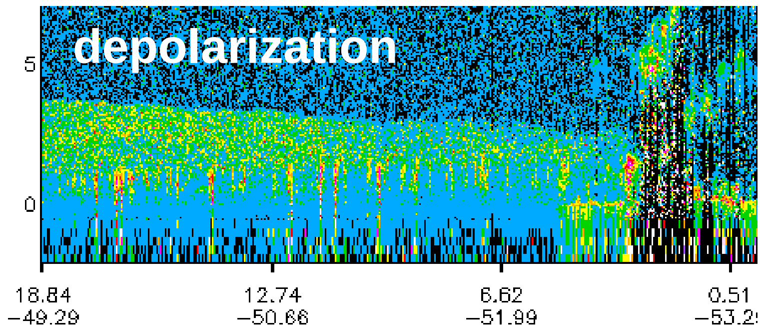
Fire locations in southern Africa from MODIS, 6/10/06



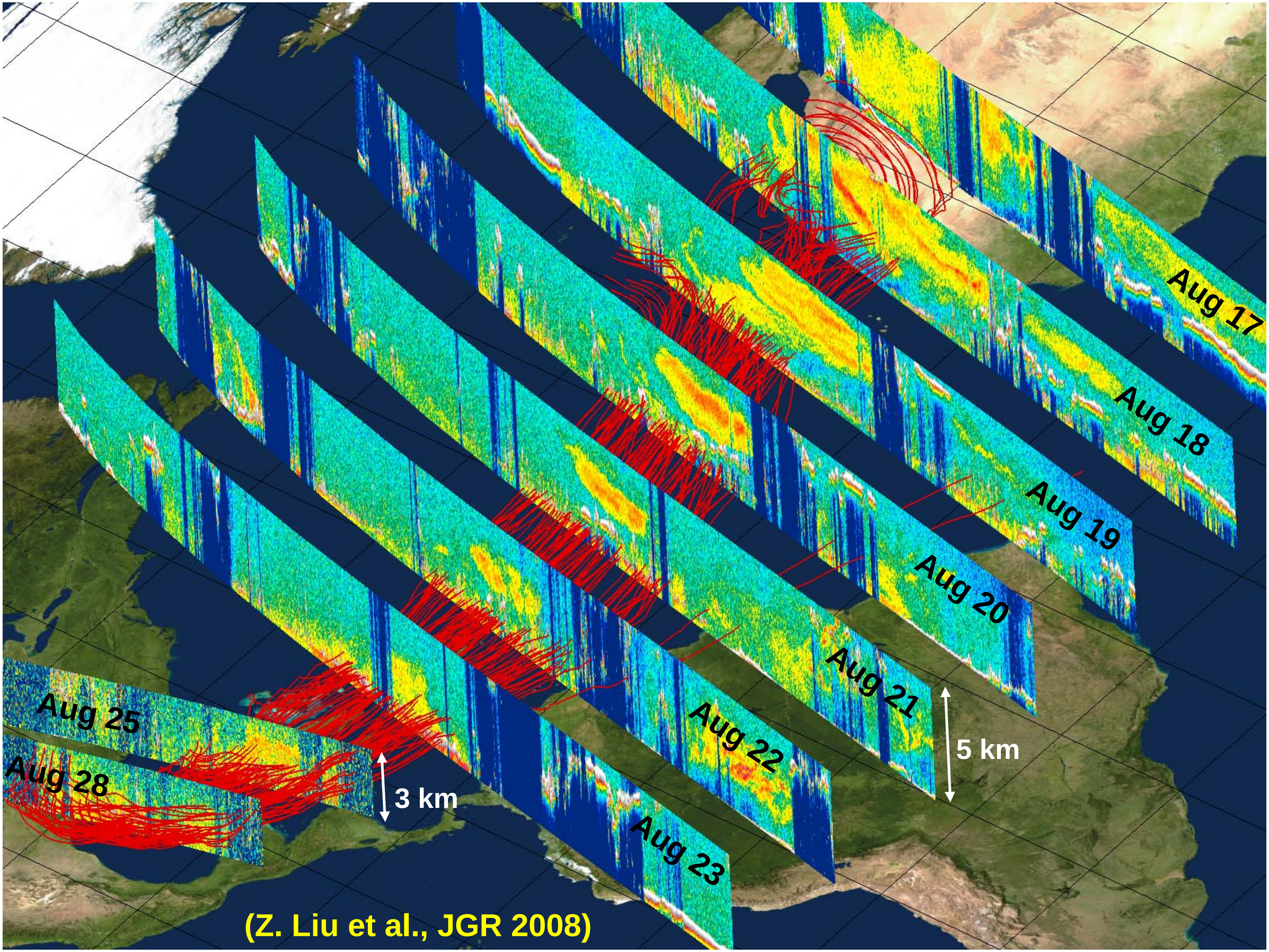
Sahara dust above marine aerosol



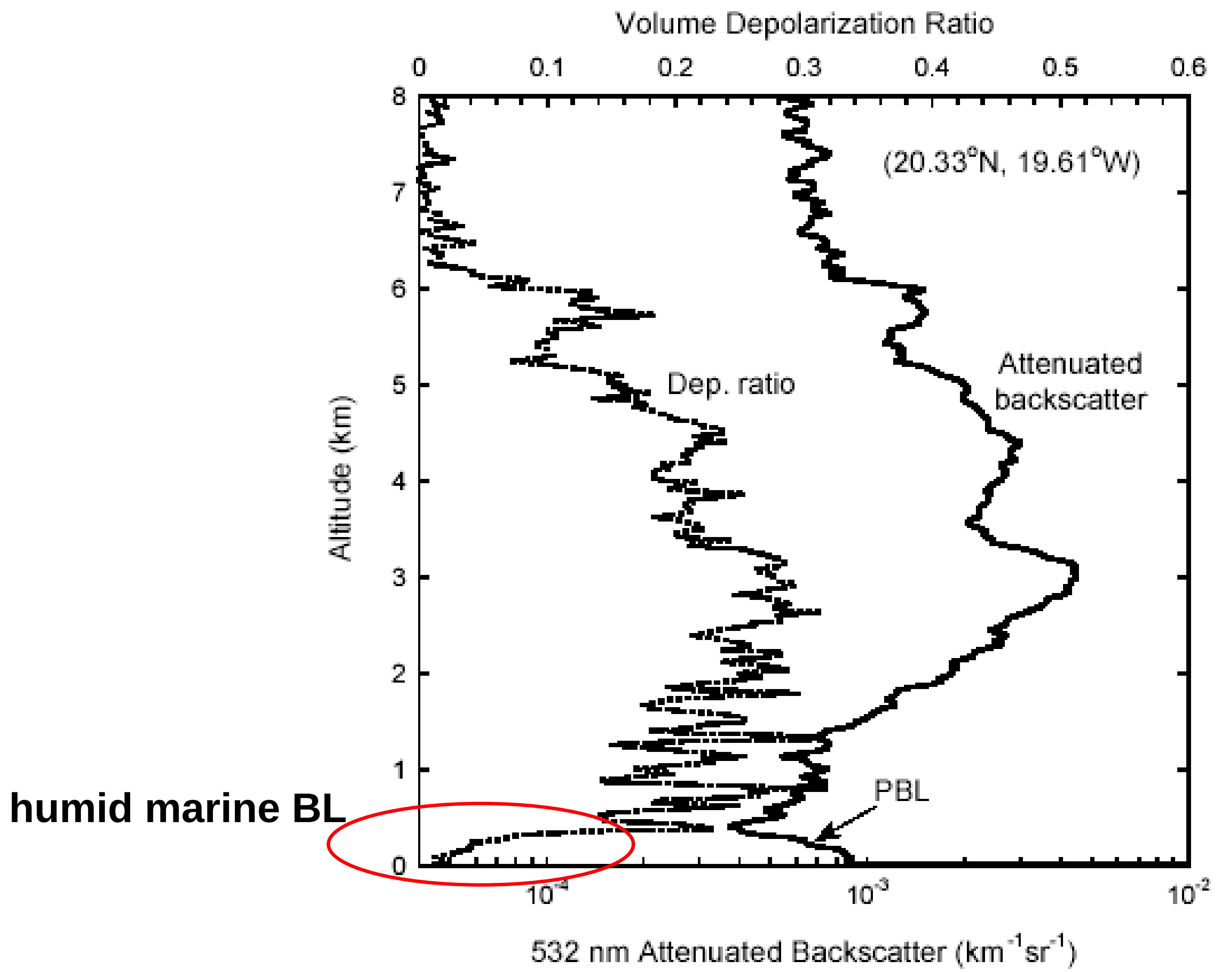




Three-channel profiles provide insight into aerosol type, mixing

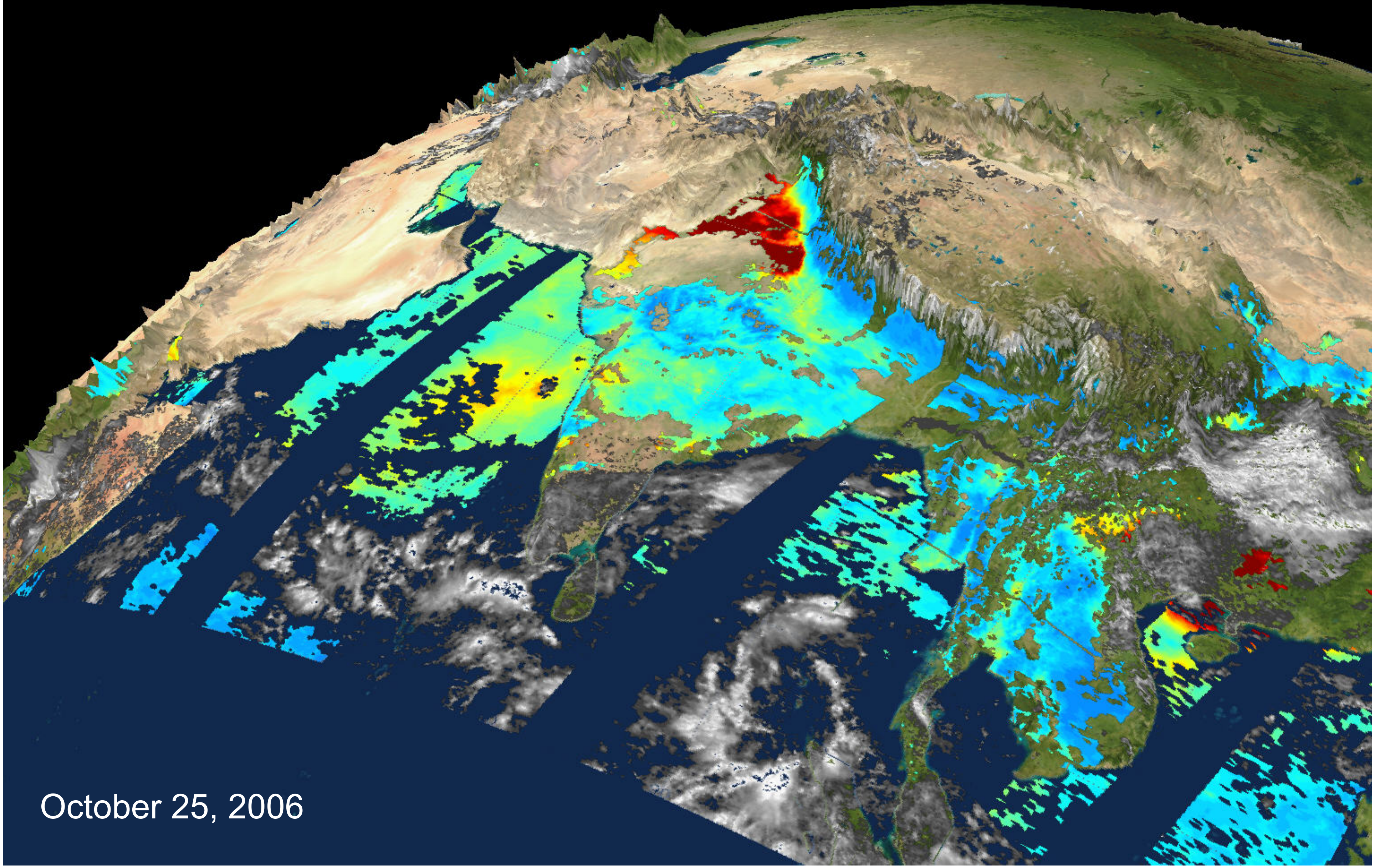

Aug 17
Aug 18
Aug 19
Aug 20
Aug 21
Aug 22
Aug 23
Aug 25
Aug 28
5 km
3 km
(Z. Liu et al., JGR 2008)

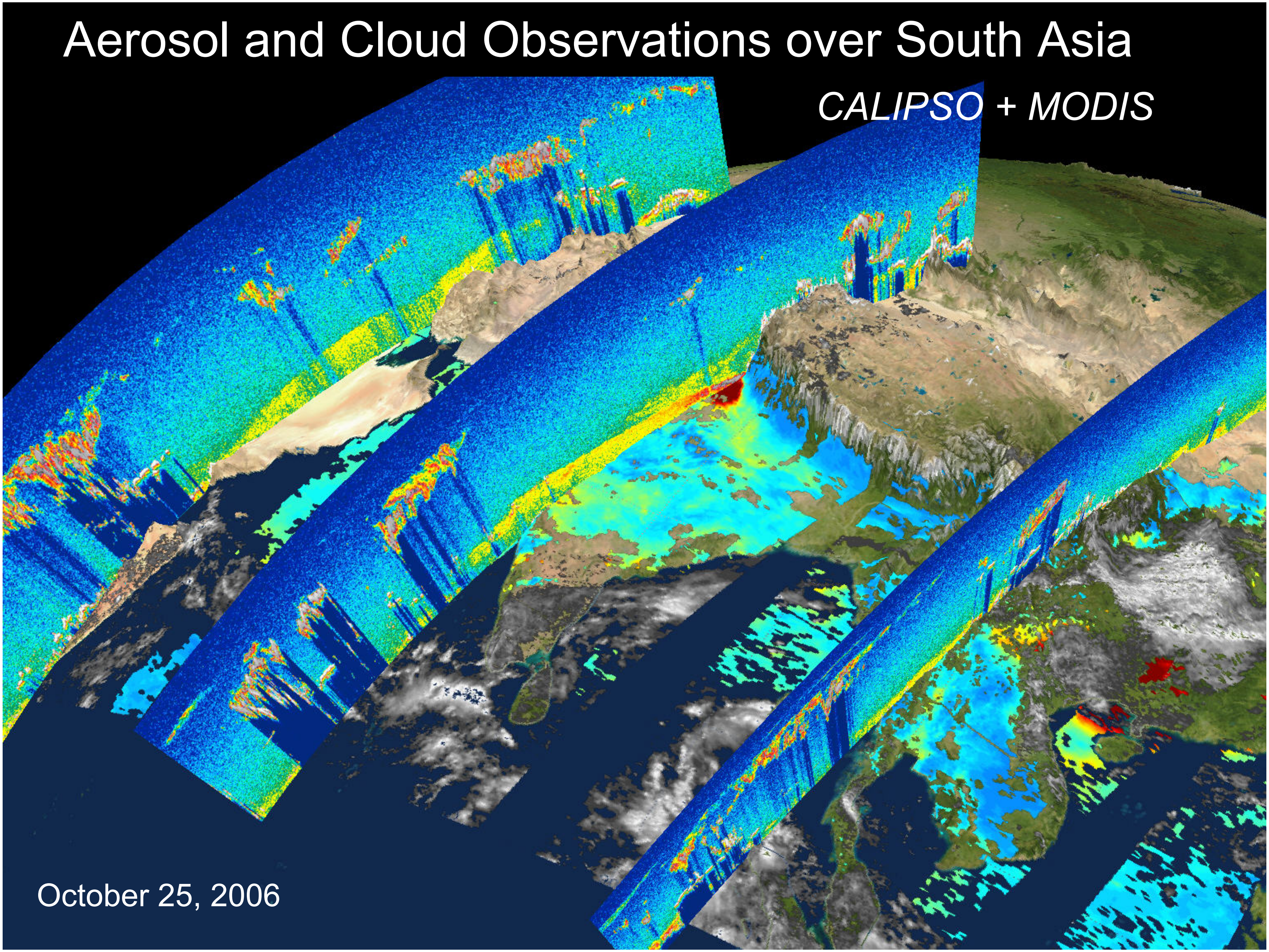
532 nm Dust Profiles from CALIOP



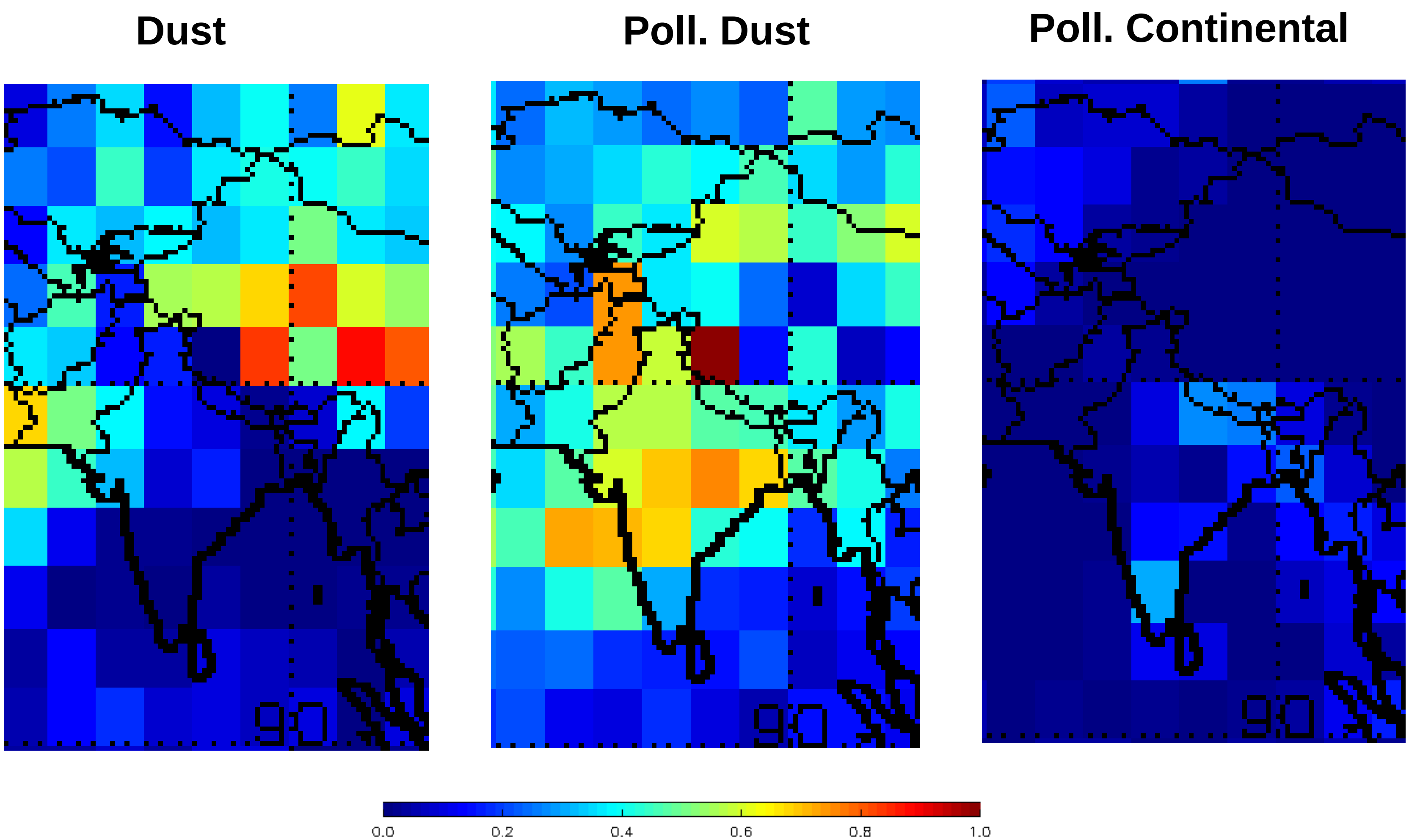
Aerosol and Cloud Observations over South Asia

MODIS




Aerosol and Cloud Observations over South Asia
CALIPSO + MODIS
October 25, 2006

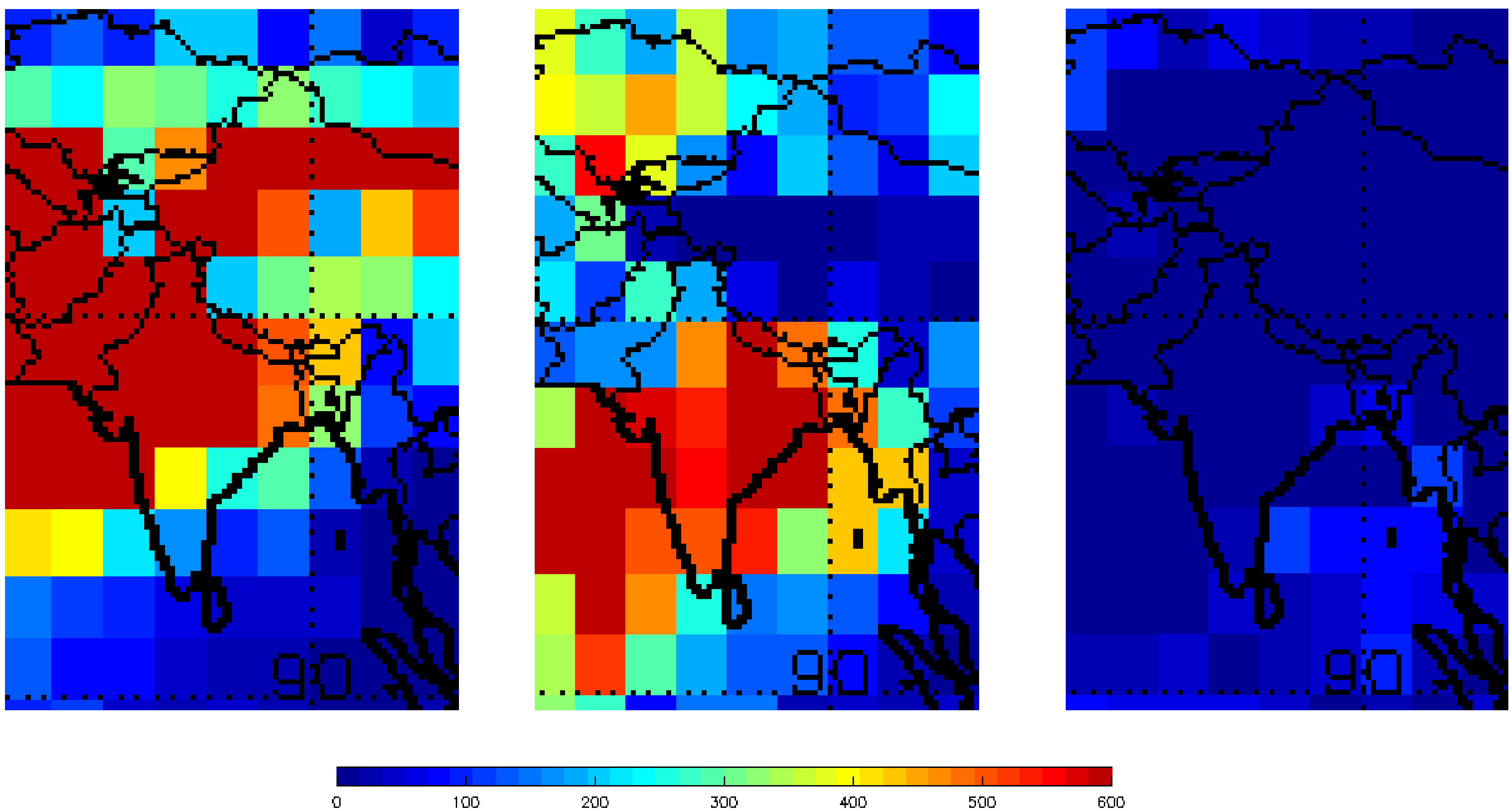
Jan 2007



fraction of observations

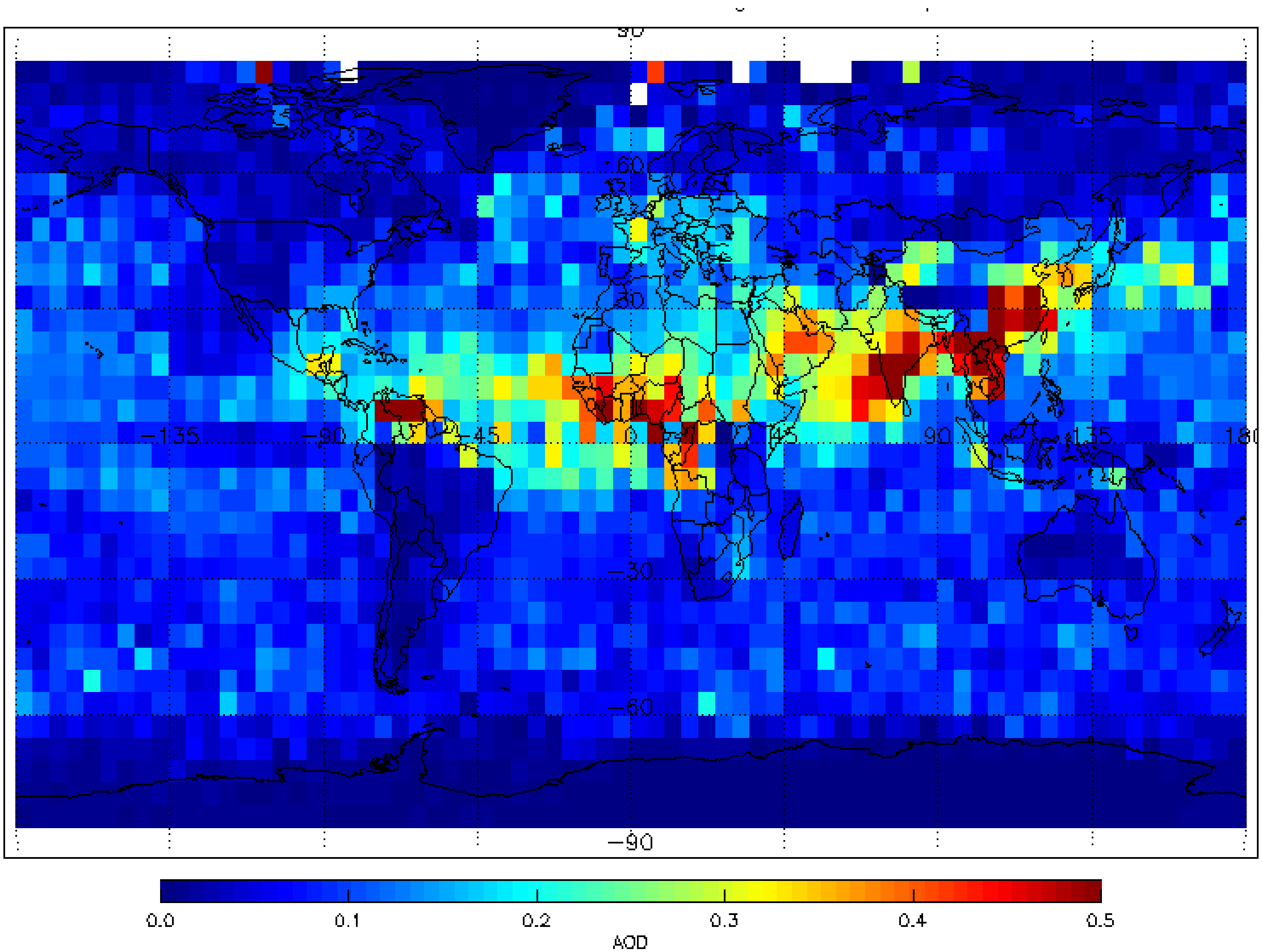
Aerosol Type, MAM 2007

Dust | Poll. Dust | Poll. Continental



number of observations

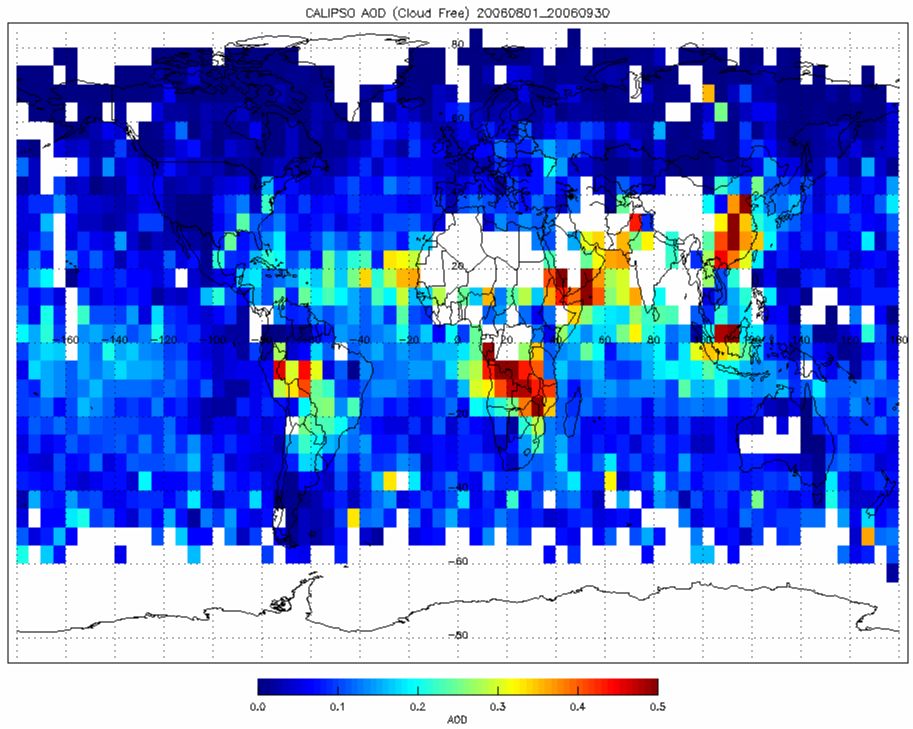
CALIPSO AOD: MAM 2007



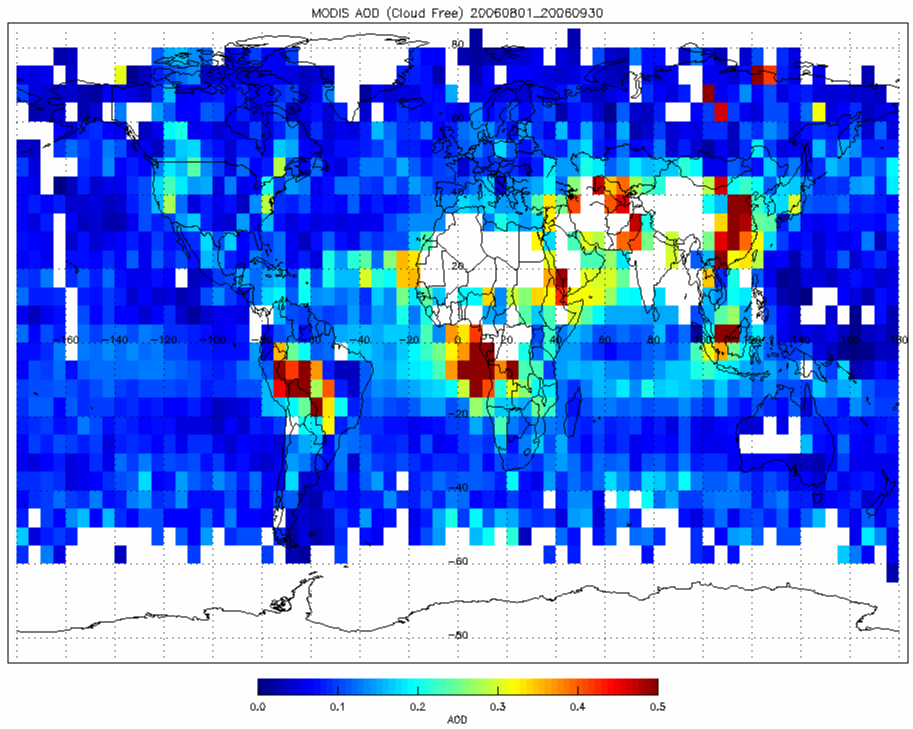
AOD, matched columns: Aug-Sept 2006

Data sources: CALIPSO V2, MODIS Collection 5 (no Deep Blue)

CALIPSO

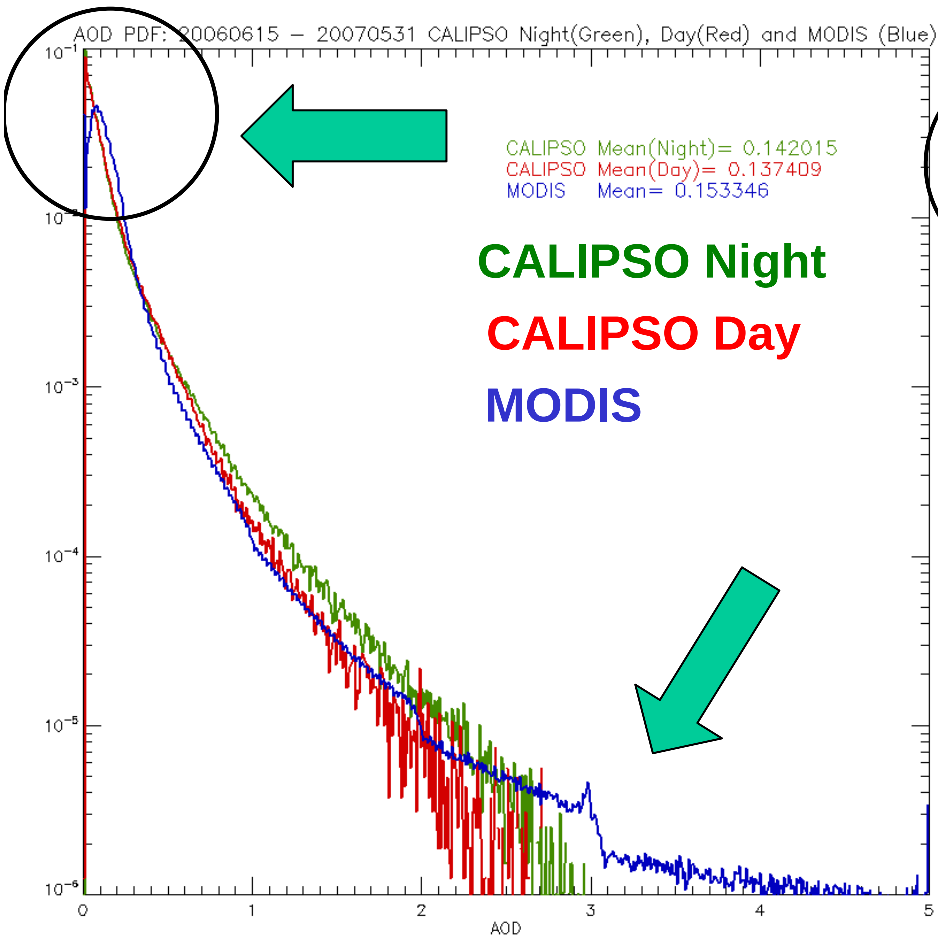


MODIS

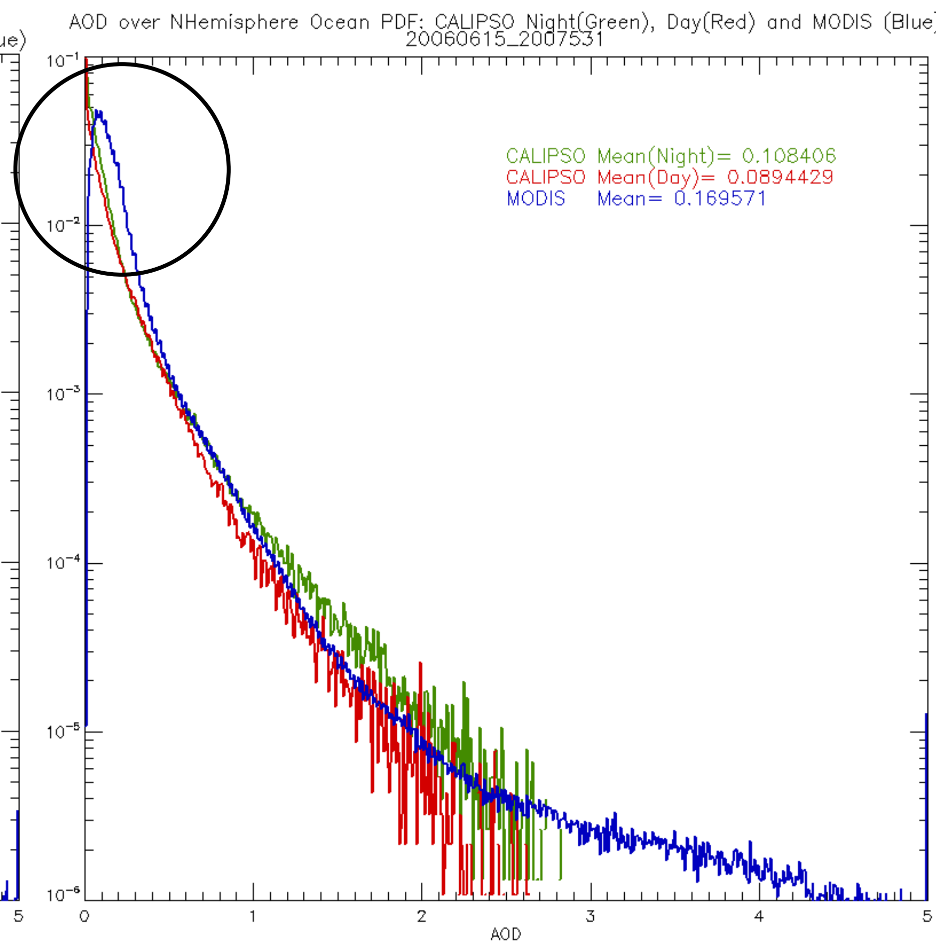


AOD, cloud-free columns: 6/06-5/07

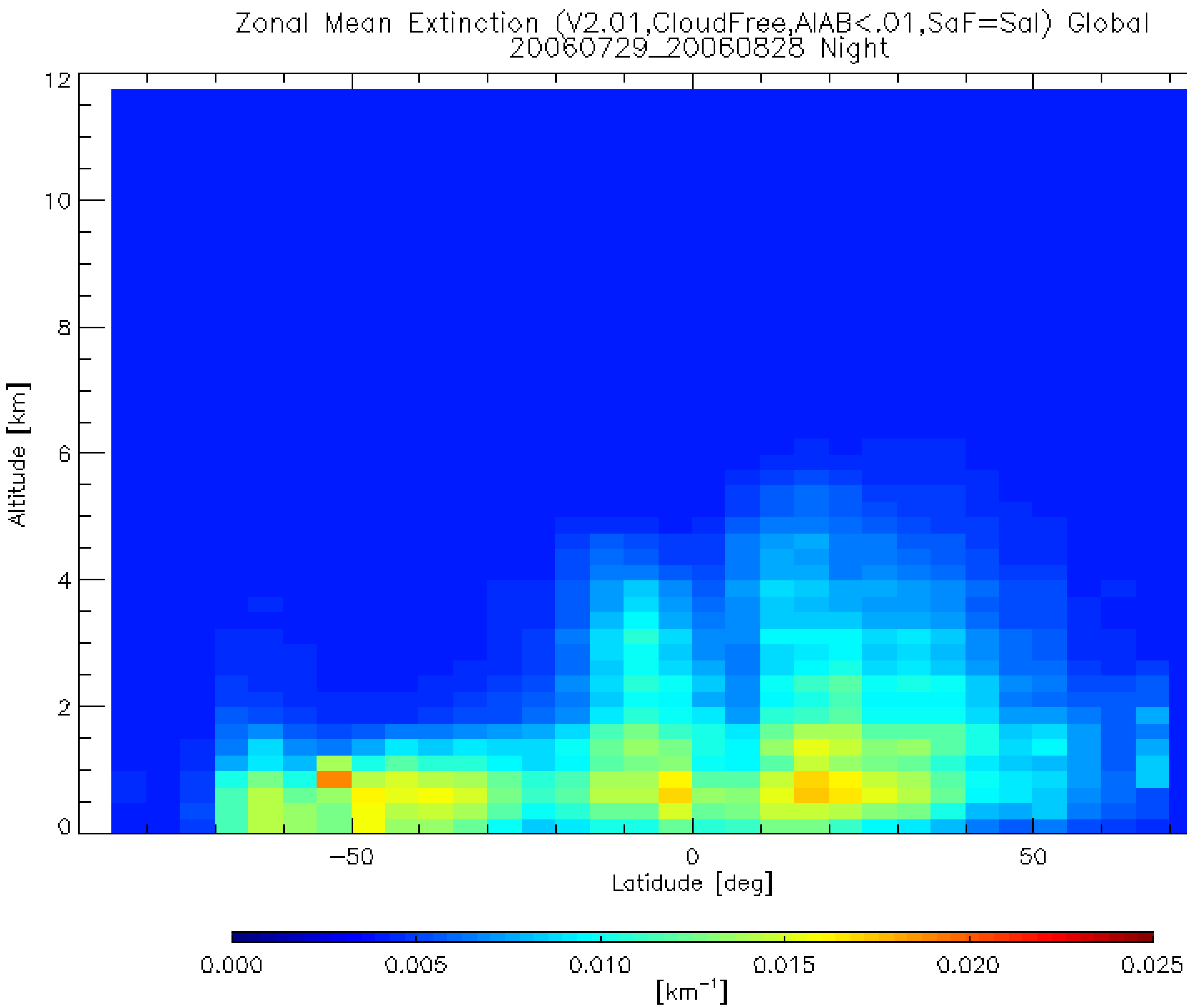
Global



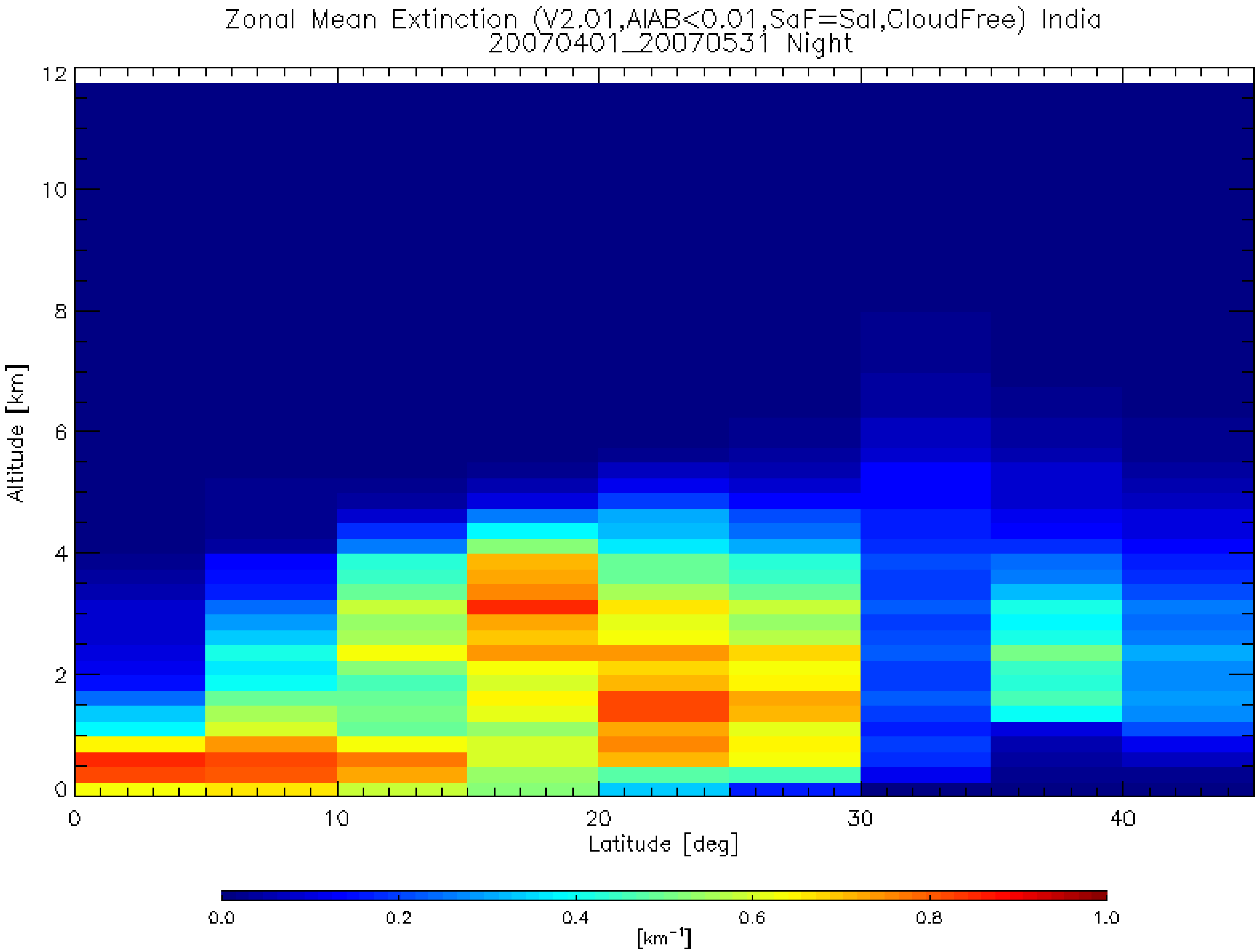
NH Ocean



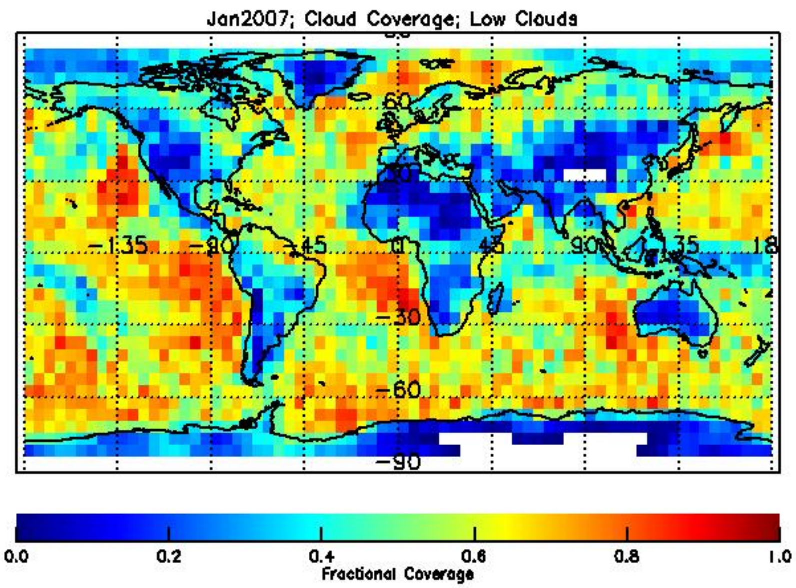
Global zonal mean aerosol extinction: Aug 2006

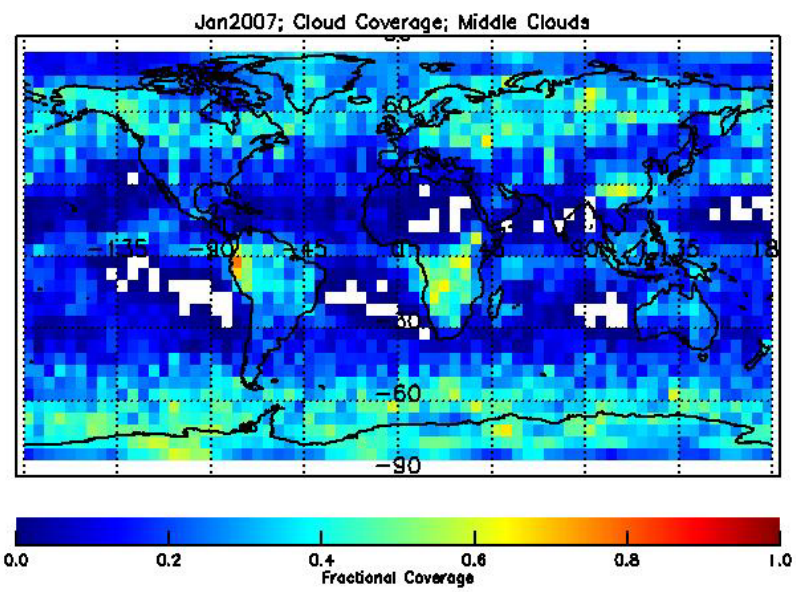


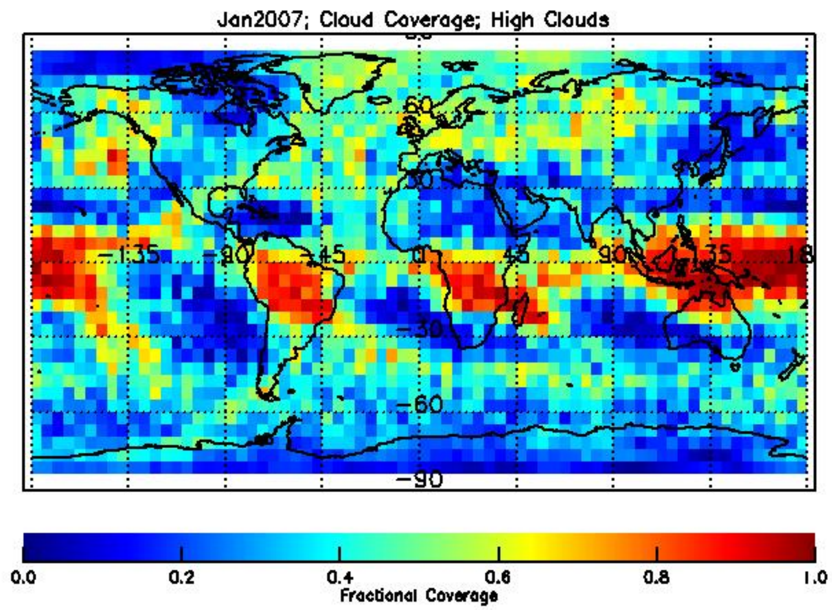
Zonal aerosol extinction, India: April-May 2007



Fractional Cloud Cover: Low, Medium, High

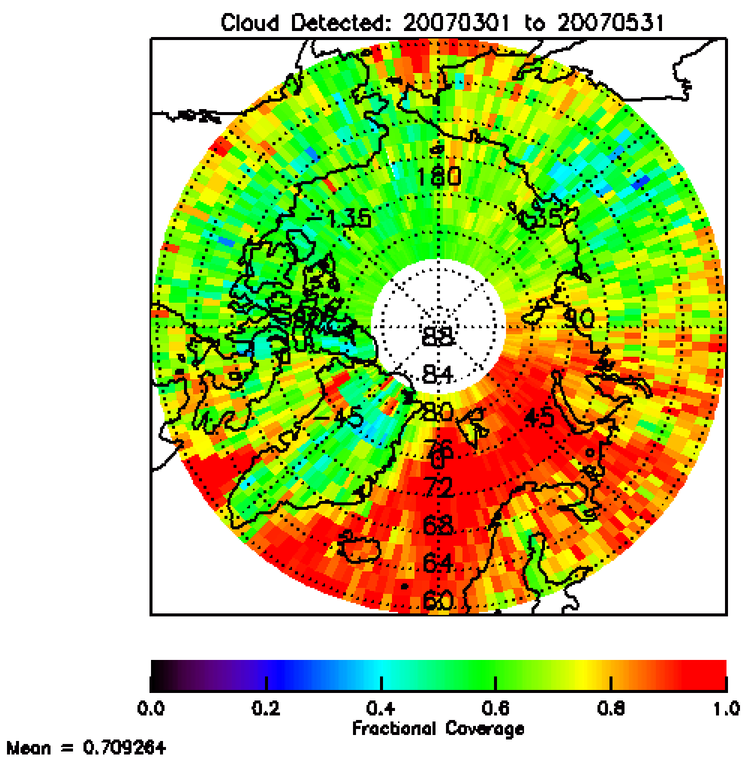


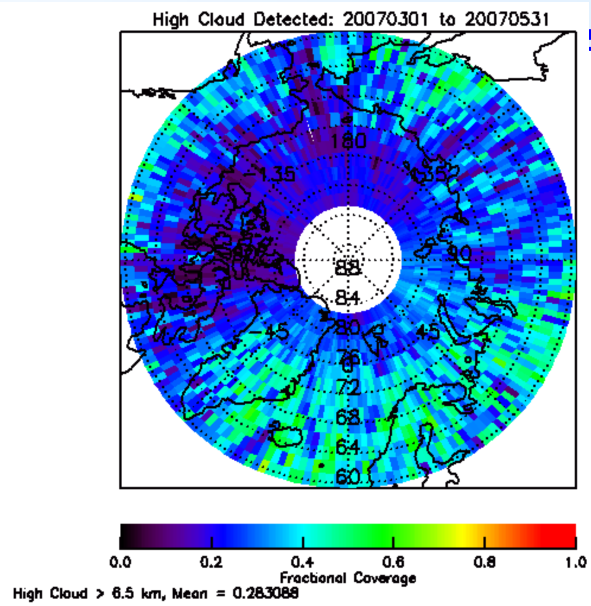




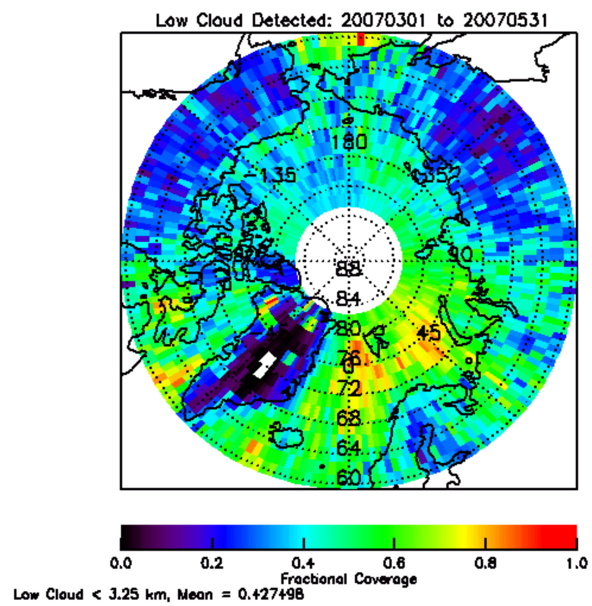
Arctic cloud: MAM

Cloud Fraction: All cloud



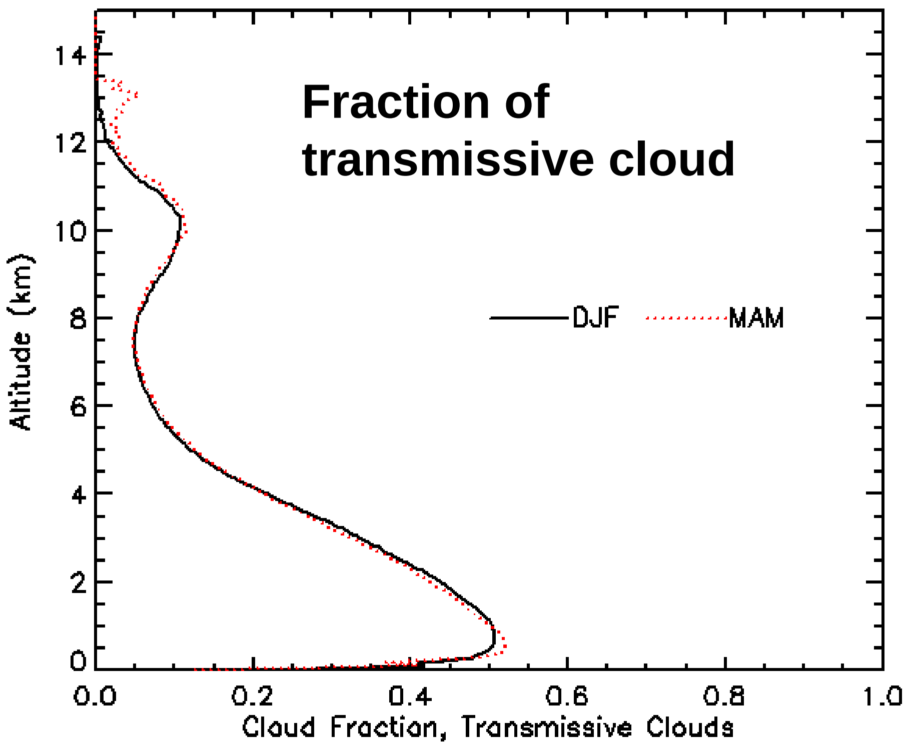


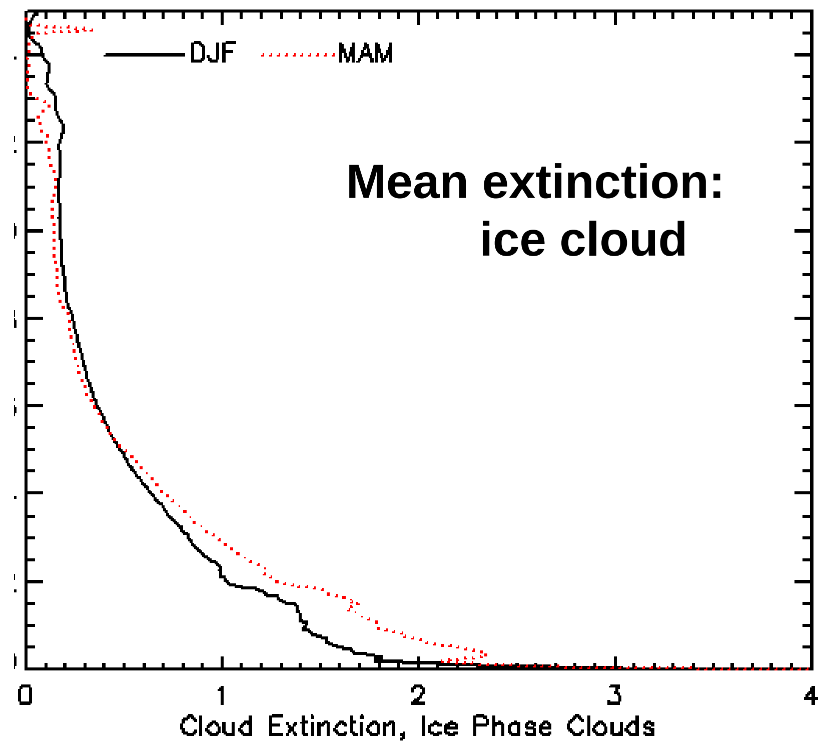
High cloud



Low cloud

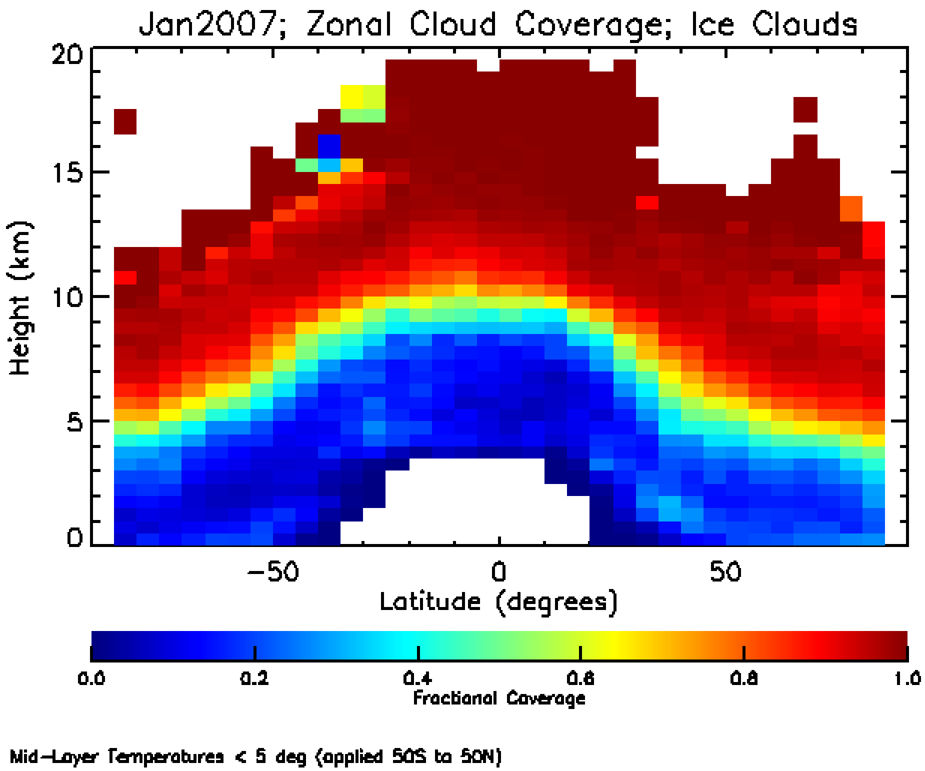
Examples from Cloud Profile Product

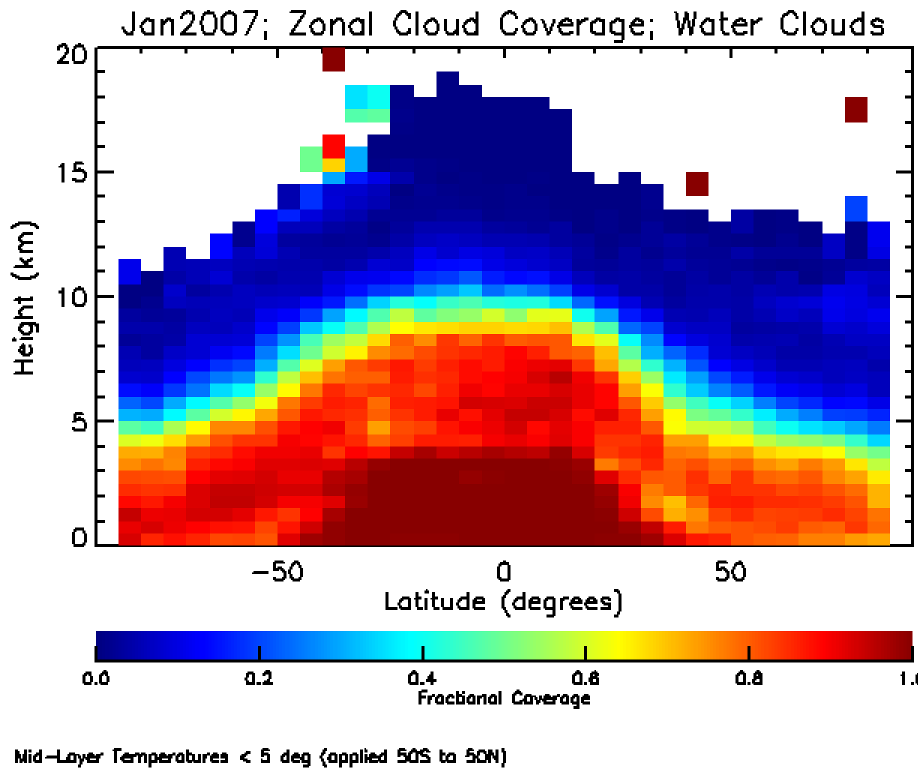




Results from cloud profile product, using scene classification and QA flags from 5-km cloud layer product

Zonal Fraction of Ice and Water, "ice clouds" > 5ºC forced to water cloud





Clouds defined as "Ice" with a mid-layer temperature greater than 5 degrees, contained within 50N to 50S, were re-defined to "Water".